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IMPLICATION OF ADDITIVE MANUFACTURING ON UNITED STATES AIR FORCE EXPEDITIONARY CIVIL ENGINEER SQUADRON SUPPLY CHAIN

THESIS

Shane R. Veitenheimer, Captain, USAF

AFIT-ENV-MS-17-M-234

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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THESIS

Presented to the Faculty

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In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Engineering Management

Shane R. Veitenheimer, BS

Captain, USAF

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Abstract

Additive manufacturing is mandated as a technology for the Department of Defense to consider to implement. Previous efforts have shown positive potential for additive manufacturing (AM) for United States Air Force Civil Engineering but do not explore the economic impact. This research examines implementation by investigating a specific Explosive Ordnance Disposal repair part supply chain in the current combat theater of operations. A framework to capture the basic financial savings AM could realize was developed to aid AM decision making.

This research established a Scenario Planning and Monte Carlo simulation based framework to produce an estimated annual cost for a system with various configurations and machine capabilities under varied machine life lengths. The model informs the baseline value of AM replacement and what this represents for an associated machine cost. Further, the research presents potential roadblocks and additional cost areas that would impact an AM decision. The overall results take the next step to understand AM's implementation for the United States Air Force and Civil Engineer Squadrons.

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Shane R. Veitenheimer

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IMPLICATION OF ADDITIVE MANUFACTURING ON UNITED STATES AIR FORCE EXPEDITIONARY CIVIL ENGINEER SQUADRON SUPPLY CHAIN

I. Introduction

The emergence and evolution of additive manufacturing (AM), or more popularly called 3D printing, raises questions for leveraging the technology in the Department of Defense (DoD) and the United States Air Force (USAF). This includes at the individual unit levels, such as home station Civil Engineer Squadrons (CESs) and Expeditionary Civil Engineer Squadrons (ECESs) deployed for combat operation. In the 2013 State of the Union address, President Obama publicly emphasized the importance of AM research to national strategy and highlighted the public-private partnership at the National Additive Manufacturing Innovation Institute (Gross, 2013).

Background

The idea of directly creating three-dimensional objects captured attention quickly when first introduced in the 1980s (Lipson & Kurman, 2013) but struggled early because of limitations in supporting technologies such as graphics cards, processing power, and computer control which had to evolve alongside AM (Gibson, Rosen, & Stucker, 2015). Industry also doubted AM in its infancy because of a lack of metal printing and the associated need for higher engineering properties (Lipson & Kurman, 2013; Mellor, Hao, & Zhang, 2014). However, AM systems' abilities now range from simple materials (laminated paper and waxes) to much more complex combinations (composites and metal alloys) (DoE, 2015; Wohlers & Gornet, 2014).

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The push toward US government involvement for innovation in AM led to investment and exploration in many areas of the DoD, ranging from simple learning application in a DoD sponsored program for at-risk youth to integration into the complex design of the F-35 Joint Strike Fighter (Tadjdeh, 2014b; Wohlers & Gornet, 2014). Further, each military branch developed or reallocated existing programs to explore the application of AM, such as the US Navy's "print the fleet" and US Army's mobile fabrication lab (Hill, 2013; Tadjdeh, 2014a). As a result of these and other efforts, the Government Accountability Office (GAO) briefed the Senate Armed Services Committee on AM's current state in 2015, with focus on the potential defense benefits and constraints, possible extent of contribution to DoD missions, and projects from America Makes which could be transitioned to DoD use (GAO, 2015b). The GAO report is summarized in Table 1.

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Table 1: Summary of the GAO's Assessment of AM for the Senate Armed Services Committee

REPORT ELEMENTS	EXAMPLES OF INCLUSION FROM DOD BRIEFING[A]
Potential additive manufacturing benefits and constraints	**Benefits:**
	• Focused logistics—the right part, at the right place, at the right time • Rapid manufacturing • Enabling of design complexity • Shortening of supply chain • Enabling of mass customization
	Constraints:
	• Need for an understanding of potential defects • Need for additive manufacturing standards (materials, process, machine, quality) • Need for improved process control and repeatability • Need for design tools for additive manufacturing components
The extent to which additive manufacturing could contribute to DoD missions or advance DoD in performing its missions	**Contributions:**
	• Strengthening of the U.S. industrial base, boosting of the manufacturing sector of the U.S. economy, and support for science, technology, engineering, and mathematics education • Enabling new lightweight designs and reducing fuel costs • Increasing operational stability of weapon systems by reducing cost and repair time
Which America Makes[b] projects will be transitioned for DoD's use	**Projects:**
	• Rapid qualification methods for powder bed direct metal additive manufacturing processes—which will be of benefit to DoD by (1) reducing time to qualify additively manufactured defense aerospace components, thereby allowing such parts to be used; and (2) reducing part weight, which reduces fuel consumption and saves fuel costs over aircraft's entire life cycle. • Qualification of additive manufacturing processes and procedures for repurposing and rejuvenation of tooling—which will benefit DOD by extending tool life, saving capital investments in tooling, and allowing shorter production lead times. • Optimization of parallel consolidation methods for industrial additive manufacturing—which will benefit DOD by reducing part production lead times by increasing production speed of 3D printed aluminum parts by 10 times.

In addition to dedicated research organizations organic to military branches, AM has been investigated by advanced academic degree programs at the Naval Postgraduate School (NPS) and the Air Force Institute of Technology (AFIT). Previous AFIT research in AM and application for CES determined AM will be useful as part of deployable kits by 2020 (Poulsen, 2015), while a separate thesis effort resulted in AM part development for an Explosive Ordnance Disposal (EOD) sensor bracket for use with bomb disposal

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robots (Shields, 2016). Other follow-on research with EOD aims to design and test AM produced repair parts for a newer bomb disposal robot model (Murphy, 2017).

AM is being explored for CESs at AFIT along with other new technologies to determine if new technologies can increase efficiency or mission effectiveness. CESs have a diverse mission set for providing public works services to USAF bases all over the world. Not only does a CES deliver base planning, development, construction, maintenance, utilities, and environmental compliance, but it also services for housing, fire protection, aircraft crash and rescue, explosive ordnance disposal and disaster preparedness (USAF, 2015c). With 12 enlisted specialties, 9 officer shred outs, and extensive DoD civilian and contractor positions, there is immense diversity and demand in the CES supply chain for repair parts (USAF, 2015a, 2015b). Several of the CES career fields are restricted by code compliance, therefore AM is not likely to replace electrically rated parts, firefighting equipment, or similar high-risk and regulated items until further testing proves these items can pass standards (Shields, 2016).

Poulsen (2015) suggested AM usefulness for use in a contingency environment. A framework to study the impact of AM on a spare parts supply chain has been developed (Holmström, Partanen, Tuomi, & Walter, 2010) and applied with different supply chain modeling techniques, but in the context of within the Continental United States where less constrained shipping options are available (Khajavi, Partanen, & Holmström, 2014; Liu, Huang, Mokasdar, Zhou, & Hou, 2014). This research aims to bridge the gap between ECES use of AM and the subsequent supply chain implication.

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Problem Statement

Past research has shown opportunities between AM and CESs, but additional information is needed to better understand implementation considerations of this new technology. A comparative model is needed to weigh the options available for AM. Appropriate simulations should show scenarios of AM application compared to the current process. Such a simulation will provide valuable information on an emerging technology which could reduce costs, whether in dollars or mission delays, specifically in a deployed expeditionary system. Previous AFIT research focused on specific AM applications rather than developing a framework for analyzing operational implementation. This research is intended to help bridge that gap.

Research Objectives and Investigative Questions

The overall purpose of this research is to investigate the effects of AM on supply chains used by ECES units and provide information for better decisions in AM application. To meet this goal, a model will be developed to compare current repair part fulfillment with likely AM implementation models with the goal of creating a flexible decision tool for deployed or remote operations managers. The overall research hypothesis is that "Additive manufacturing is a technology which should be integrated with other supply chain fulfillment methods in Expeditionary Civil Engineer operations and that the costs can be estimated to compare with traditional methods." To test this hypothesis, three investigative questions were posed:

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1. *How can Expeditionary Civil Engineer Squadrons define current supply chain fulfillment methods?*

This question explores how to capture current repair part supply chain fulfillment methods with the hypothesis that the system of a specific ECES supply chain can be defined and realistically modeled in order to establish a framework to support AM decision making.

2. *How would Expeditionary Civil Engineer Squadrons most likely implement AM in a contingency operation theater?*

This question explores the ways in which AM would be configured within a contingency theater in terms of locations of AM machines; the hypothesis of this research is that an existing framework and literature exists to provide guidance to AM implementation configuration.

3. *How would an AM-enhanced supply chain fulfillment compare to current supply chain fulfillment for Expeditionary Civil Engineer Squadrons?*

This question explores the differences between current supply chain activities and those that could be realized through AM, with the hypothesis that this can be compared using traditional supply chain modeling techniques adjusted to appropriate AM considerations.

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Thesis Overview

The remainder of this thesis is organized in a five-chapter format. After this introductory chapter, the literature review in Chapter II first gives a broad definition and context of supply chain and its importance to for military operations. Then, the AM processes and the universal steps for AM are shown with established advantages of AM categorized into two key supply chain terms. The challenges for implementing AM are then highlighted and addressed based on industry trends. This is followed by a review of AM cost modeling and cost per part proportions to understand what drives AM's primary costs. Finally, established research combining supply chain theory with AM is highlighted for the framework used. Specifically, scenario planning and a traditionally accepted supply chain modeling technique, Monte Carlo simulation.

The methodology found in Chapter III lays out the Monte Carlo model used to capture part and intratheater transportation costs associated with a specific ECES repair system's current operations. The chapter discusses the model and how it incorporates potential impact of AM on the EOD bomb disposal robot repair system defined. The chapter begins by defining the system considered for this research with respect to locations and equipment modeled, then compares with costs used in previous research using a similar framework. The scenarios considered for this research are also defined and the data used for transportation costs and repair information is introduced. Finally, the inputs, outputs, and dynamics of the model are described.

Chapter IV presents the results of the Monte Carlo simulation to identify the trends of the model and discuss the interpretation of the observed differences between repair scenario costs. Wrapping up, Chapter V relates the results of the literature review

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and simulation back to the investigative questions to understand the potential implication AM has on ECES supply chains. In this final chapter, conclusions, limitations, and significance of the research are discussed to provide recommendations for action and future research in AM and supply chains.

Implications

The framework developed as a result of this research could be a positive step to understand individual AM applications in order to build a better whole-picture view of AM implementation in the DoD. This research attempts to build on concepts of Holmström et al.'s established AM research model and, because of the diverse missions of USAF units, could put the USAF in a position to further explore the model's assertions that acting more like an AM logistics service provider is the ideal position in the evolving supply chain configuration, rather than an original equipment manufacturer or end-user. The original research suggests logistics service providers will be in the best position to leverage the benefits associated with AM because of the maximization of machine utilization rates across multiple and diverse end item manufacturing that is close to the point-of-application (Holmström et al., 2010).

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II. Literature Review

Chapter Overview

This chapter covers a review of articles and research used to guide this investigation. It provides a definition and context of supply chain and its importance in military operations. Then, the AM processes and steps used across all of them are shared, with the recognized AM advantages discussed and categorized into supply chain terms. This is followed by the challenges to implement AM and exploration of the direction the industry is heading to meet these roadblocks. Next, the common cost models used to determine the primary costs of AM are examined to understand how AM costs are distributed in order to determine a possible way to estimate machine purchase cost. Finally, established research combining supply chain theory with AM is highlighted for the framework of using scenarios and supply chain modeling techniques, leading to background review of scenario planning and Monte Carlo simulation.

Supply Chain

The DoD manual on supply chain management, DoDM 4140.01, defines supply chain as "the linked activities associated with providing materiel from a raw material stage to an end user as a finished product" (p. 11), to include consideration of "processes of plan, source, make and maintain, deliver, and return" (p. 5). The modern concept of supply chains, in relation to manufacturing and mass production, developed initially with the advent of more efficient transportation which coupled with the cost benefits of economies of scale to be profitable (Baldwin, 2012). Further, the leveraging of technology for cost efficiency continued with the introduction of information and

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communication technologies, which allowed for economically justifying the offshoring of jobs (Baldwin, 2012). Thus, the precedent is established for the wide-sweeping effect of technology on supply chains.

Military Supply Chains

The movement of men and supplies has been a vital consideration throughout the history of armed conflict (Antill, 2001). Although the terms logistics and supply chain are relatively new, they find their roots in military science and contingency operations (Supply Chain OPZ, 2013) and continue to be an important aspect of modern militaries (GAO, 2015a; NATO, 2012). Lessons learned from recent US military conflicts with full-scale deployment–Operations DESERT SHIELD, DESERT STORM, and ENDURING FREEDOM–highlight the difficulty of modern mass military movements given short timeline requirements (Haulman, 2002; McCormick, 2009). During initial combat operations, priority is given to combat personnel and personnel sustainment requirements such as ammunition, rations, etc. As a result of the limited airflow capacity, the lack of repair parts and equipment hindered military efficiency and effectiveness (McCormick, 2009).

Many attempts to improve DoD mobility and supply chain have taken place over the years, such as the *AF Spare Campaign*, the creation of TRANSCOM, the reorganization and upgrade of the Defense Logistics Agency, introduction of expeditionary force deployment, modernization of equipment, aircraft, and processes, and publishing the 2014 *Strategy for Improving DOD Asset Visibility* (GAO, 2015a; Harps, 2005; Haulman, 2002; Mansfield, 2002). But the GAO has maintained DoD supply chain management as a component of the High Risk List since 1990, and in 2015 highlighted

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specific weakness areas of inventory management, materiel distribution, and asset visibility for the over $90 billion in secondary inventory items (GAO, 2015a). Each attempt to improve DoD supply chains focuses on the same two goals established by doctrine from the USAF-level through Joint and NATO, which are (1) increased flexibility to enable missions and (2) increased efficiency in carrying out this mission (GAO, 2015a; NATO, 2012; USAF, 2011). AM has been speculated as a potential technology that could help meet these goals.

Additive Manufacturing

AM processes are a family of techniques which create objects by combining layers of material, either through fusion or bonding. Wohlers & Gornet (2014) provide an overview of the history of the AM industry. The roots of AM derive from the creation of photopolymer resin in the 1950's. However, it was not until the development of the first successful AM process of stereolithography in 1980s that the industry really began. The first commercialized system came online in 1987; since then the industry has expanded greatly with the creation of a wide range of material options and the addition of six more processes defined in the standard from the American Society for Testing and Materials (ASTM) international. The ASTM Processes are summarized in Table 2: ASTM Classification of AM Processes**(DoE, 2015)**.

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Table 2: ASTM Classification of AM Processes (DoE, 2015)

Powder Bed Processes	Thermal energy selectively fuses regions of a powder bed
Directed Energy Deposition	Focused thermal energy is used to fuse materials by melting as the material is being deposited
Material Extrusion	Material is selectively dispensed through a nozzle or orifice
Vat Photopolymerization	Liquid photopolymer in a vat is selectively cured by light-activated or UV polymerization
Binder Jetting	A liquid bonding agent is selectively deposited to join powder materials, and then product is baked in an oven for final curing
Material Jetting	Droplets of build material are selectively deposited
Sheet Lamination	Sheets of material are bonded to form an object

The first ASTM international standard published by committee F42 designated Additive Manufacturing as the official term for what many formerly termed “three-dimensional printing,” “rapid prototyping,” and other names that described specific applications (ASTM International, 2015b). AM includes any of the seven distinct processes from Table 2 which are used to create objects by combining layers of material through fusing or bonding. Gibson, Rosen, and Stucker (2015) describe in detail each process which comprise individual chapters of their handbook, but each process follows the same basic eight steps:

1. Design file creation through computer-aided design
2. Design file conversion to printable format
3. Design file transfer to AM machine
4. AM machine setup and configuration, e.g. material load or setting resolution
5. Object build within AM machine
6. Removal of object from AM machine
7. Post-processing, e.g. removal of support structure or excess material
8. Final application preparation, e.g. final detailing, painting, or polishing

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AM is often presented as a promising but complicated topic and has resulted in individual research efforts and organization published status updates, such as the Wohlers annual state of the industry report, as well as AM summaries produced by interested government organizations, such as the GAO and DoE (DoE, 2015; Gao et al., 2015; GAO, 2015b; Gartner, 2014; Wohlers & Gornet, 2014). Wohlers (2014), for instance, details a thorough history of how companies entered the market and when new processes or variations of technology and materials were introduced as well as costs of machines and materials from each category. Wohlers also showed AM manufacturers reported 29% of their machines' produced parts are being used for functional parts for various industries, to include motor vehicles, military, mechanical, and electronics, to name a few. In a different overview, Bechthold (2015) provides a qualitative review into AM and presents the current state, opportunities, and challenges of AM for industrial production and the consumer markets. Finally, Mellor et al. (2014) suggests guidance is available for AM implementation in terms of strategic, technological, organizational, operational, and supply chain factors. Many AM reports present large lists of advantages, challenges, and advancements in AM, so the following sections will explore and summarize some of these key takeaways found in the literature.

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Advantages

Literature shows several main industries already successfully leverage AM, most notably automotive, aerospace, and healthcare, however, the consumer market has recently propelled AM even further with introduction of low-cost machine development for personal use (Bechthold et al., 2015; Campbell, Bourell, & Gibson, 2012; Wohlers & Gornet, 2014). Each of these industries has adopted AM for different reasons: the adaptability of AM saves time for the automotive industry by manufacturing parts during the spin-up of specific tooling; the complexity, performance, and weight characteristics have driven AM's use for aerospace; and the customization to each consumer has been the key driver in healthcare as shown in AM prevalence for dental braces and crowns, hearing aids, and limb prosthetics, as well as the growing technology of bioprinting (Bechthold et al., 2015; Campbell et al., 2012; Chua & Yeong, 2015; Gibson et al., 2015; Lipson & Kurman, 2013).

Lipson and Kurman (2013) summarized recurring themes from interviews with companies successfully using AM, and organized them into their "*Ten Principles of 3-D Printing*." Similarly, Holmström, Partanen, Tuomi, and Walter (2010) created a list of the "*Fundamental Features of AM*" as part of their research. Both lists attempt to capture the benefits of AM, but each advantage from either list can be related to one of the two goals of supply chains identified above, increased flexibility and increased efficiency. Table 3 and Table 4 below show each advantage and how it could be categorized between the two supply chain goals.

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Table 3: Lipson and Kurman's (2013) *10 Principles* Categorized into Supply Chain Goals

Flexibility:	**Efficiency**:
Complexity is free: costs are the same to print simple designs as intricate ones	*No assembly required*: costs of assembly can be eliminated
Variety is free: costs are the same to print the same thing, or multiple things	*Zero lead time*: no need to predict demand for it to be filled quickly
Unlimited design space: virtual design space can be considered infinite	*Compact, portable manufacturing*: printers require much less space than traditional storage
Zero skill manufacturing: click-to-print requires no skill	*Less waste by-product*: additive processes reduce waste in production and some are recyclable
Infinite shades of materials: multi-material printers can combine any variation of colors	*Precise physical replication*: design files do not degrade with any number of prints

Table 4: Holmström et al.'s (2010) *Fundamental Features* Categorized into Supply Chain Goals

Flexibility:	**Efficiency**:
Small production batches are feasible and economical	*No tooling is needed significantly reducing production ramp-up time and expense*
Possibility to quickly change design	
Design customization	*Possibility to reduce waste*
Allows product to be optimized for function	*Potential for simpler supply chains; shorter lead times, lower inventories*
Allows economical custom products (batch of one)	

The *10 principles* or the *Fundamental Features* can be misleading if applied to an industry with a much different baseline, such as traditional lead time of a day vs. one or

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more months, but Lipson and Kurman (2013) propose that each principle will become more proven as AM technologies are further developed and standardized. Flexibility and efficiency are also two of the four pillars identified in Grimm's 2012 four pillars for ideal AM applications. Since AM's benefits could support the goals of DoD logistics, there is further support to explore the implications for USAF applications but the potential roadblocks must also be understood.

Implementation Challenges

The challenges for AM can be generalized into three areas: AM machine capabilities, supporting technology, and policy. Many research institutions are focused on solving these issues because of theoretical advantages of AM in general or for specific uses, and some companies have solved some of them but maintain control of proprietary information to keep a competitive advantage (Gornet, 2017). This section describes each challenge area and discusses the ways that the AM industry is addressing the issue or how DoD policy and procedures could affect implementation.

Additive Manufacturing Capabilities

The first problem area regularly pointed out for AM is concern with the capabilities of the AM processes themselves: resolution, speed, build volume, scalability, material heterogeneity, or print reliability and potential defects (DoE, 2015; Gao et al., 2015; GAO, 2015b). AM's potential is seemingly in a constantly increasing and evolving state, with research specifically targeting challenge to implementation areas as well as the applications and impacts of AM (Gao et al., 2015). New processes are being researched and commercialized, such as continuous liquid interface production, or CLIP, for increased AM speed and laser-based direct-write for embedded electronic circuits

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(Piqué et al., 2005; Tumbleston et al., 2015). Additionally, the established processes are getting a fresh look with 20-year patent expirations; many experts point to the 2007 patent expiration of Stereolithography, and subsequent others since, as the reason personal printers have gone from an almost non-existent market in 2007 to more than 278,000 sold in 2015 (Gibson et al., 2015; Millsaps, 2016). Increasing metal printing options have made commercial printers more viable for industries and resulted in a 75% increase in metal printer sales from 2012 to 2013 (Wright, 2016).

Supporting Technology

Some of the issues of machine capability are closely tied to limitations of supporting technologies which greatly affect the concerns associated with process control and repeatability, available finishes and materials, and modeling accuracy (DoE, 2015; Gao et al., 2015; GAO, 2015b; Gibson et al., 2015; Lipson & Kurman, 2013). Supporting technologies have also seen incredible advancement since AM's inception. The increase in research into AM has been able to introduce better controllers and feedback systems to AM machines, and helps increase automation and repeatability of AM prints (Huang, Leu, Mazumder, & Donmez, 2015; Rauch, Hascoët, Simoes, & Hamilton, 2014; Tapia & Elwany, 2014). Since the industry was established, each year new materials have been created based on an application industry's recognition of AM's potential and the subsequent need for specific properties, processes, or printers as seen in the example of custom software and printers created for the dental industry (Gibson et al., 2015; Wohlers & Gornet, 2014).

It could take multiple AM machines to produce each part of a complex and fully integrated product, but available AM machines can produce PC control boards and

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electronics, flexible and wearable materials, and strong structural parts with optimally designed internal cavities or channels (Gao et al., 2015; Lipson & Kurman, 2013; Rayna & Striukova, 2014). The increasing processes and variety of industries taking on AM is paving the way for combinations of parts production in end-user products which further supports the applicability for CES or ECES units.

Policy

Finally, several policy areas are deficient and create potential roadblocks to AM use for the DoD. Specifically, there is a lack of testing standards for materials and quality, a lack of safety validation standards for critical parts, and numerous concerns with protecting intellectual property associated with design open sourcing and replication from 3D scanning (DoE, 2015; Gao et al., 2015; GAO, 2015b; McLearen, 2015; Shields, 2016). The need to create standards became apparent with the expansion of the AM market over the last decade and as AM direct manufacturing gained traction as a method of producing end-use products. The standardization of AM began in 2009 by the ASTM international committee, which teamed with International Organization for Standardization (ISO) in 2011 (Wohlers & Gornet, 2014). ASTM international has approved several definition and testing standards but only has eleven of thirty plus standards published, while ISO has six of its twelve planned standards adopted (ASTM International, 2015a; ISO, 2016). As standards are approved, the legitimacy of AM as a direct manufacturing process is further maturing, paving the way for new industries and applications (Gibson et al., 2015; McLearen, 2015). The creation of standards for testing and technology improvements address some of the policy concerns with AM.

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Another policy concern is intellectual property. Intellectual property is not a new concern for USAF or DoD acquisitions because of AM, and has been asserted as "one of the most complicated issues in acquisition management" (Murray, 2012). The focus of intellectual property is very apparent in the procurement of entire weapon systems platforms because of their high value (Murray, 2012). The desire to keep the rights to this information is understandable for contractors that put money into the development and production of original systems with the expectation of recouping these costs (Erwin, 2012). However, companies working with the DoD understand the leverage of charging more for the technical data of their products (Erwin, 2012). For this reason, there is no excuse for the DoD, or USAF, to not pursue AM designs on the basis of intellectual property of the digital design rights. Instead, the acquisition of AM design should be treated as specific section of an acquisition plan or as its own effort, with its own cost to obtain engineering designs, similar to construction architect and engineering indefinite delivery/indefinite quantity contracts or their kin. Not only would this help address intellectual property concerns, but would include engineer approved design for a specific desired function and AM machine which could further simplify the adoption of AM.

No matter what the advantages and challenges of AM may be, like industry, the DoD is not likely to fully embrace the technology without understanding the financial considerations of implementation. The next section of reviewed literature will explore how costs of AM are captured and presented in past research.

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Modeling Cost

Creating a flexible model to inform AM implementation decisions in a repair part supply chain is complicated by not having a specifically defined part or parts. Because there is not a known material quantity or specifications to drive the selection of a specific type of AM machine, it is difficult to define key parameters such as material type, material usage, printer build rate, etc. The majority of AM research available lacks economic implications for AM, but instead is mostly focused on technological implications (Weller, Kleer, & Piller, 2015).

As a result, a limited number of cost models exist, each with their own focus and assumptions, but these commonly assume 1) there is a single, well-defined part being produced and 2) there is a fixed annual utilization rate when calculating machine input to the cost per part, generally either 90% and 57% (Lindemann, Jahnke, Moi, & Koch, 2012; Thomas & Gilbert, 2014). Though somewhat limited by these assumptions, these methods have been valuable in understanding the impact of AM's break even points compared to traditional manufacturing, namely showing when economies of scale let traditional manufacturing take the lead as can be seen in a summative review of several research efforts (Gebler, Schoot Uiterkamp, & Visser, 2014). Labor, material, and machine costs are accounted for more often than more difficult to define, or "ill-defined," costs associated with areas such as proximity to production, vulnerability to disruption, inventory, and supply chain; but common models have shown that labor costs are less than 2-3% of part costs and are not as significant as material and machine costs (Thomas & Gilbert, 2014).

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Lindemann et al. (2012) attempted to combine the primary two models with several additional accepted AM cost modeling techniques to increase the robustness of their research. They performed sensitivity analysis on building rate, utilization rate, material costs, and machine investment costs to capture the relative percentage the total cost of part for different cost factors. The ratio of machine purchase cost to the total part cost was consistently the highest and ranged from 45%-78% with an average of 65% for metal parts (Lindemann et al., 2012). The average cost of industrial AM machines dropped 51% from 2001 to 2011, but the percentages found by Lindemann et al. were not less than similar research by Hopkinson and Dickens (23%-75%), even though the period between the research was over a similar span (2003 to 2012) (Thomas & Gilbert, 2014), indicating this is likely to be a continued trend.

This may be because as AM machines become cheaper the other cost factors are also evolving with cheaper materials and more efficient builds for various reasons. For plastic parts the variance has been shown to be less but is within the range seen by metal parts, 59%-66% (Atzeni, Iuliano, Minetola, & Salmi, 2010). Though specific costs for AM machines and AM parts are difficult to estimate without designs and specifications, the percentage invested into an AM machine should reasonably be expected to fall within these ranges, and could be roughly estimated at the average of 65% seen for metal parts, as it would be close to that seen by plastic parts as well.

Additive Manufacturing and Supply Chain: Scenario Planning

In review of literature exploring AM and supply chains, the use of scenario planning with established supply chain modeling has been effective to explore AM's

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relationship to established fulfillment of repair parts (Khajavi et al., 2014; Liu et al., 2014). Scenario planning was useful in countering uncertainties in demand forecasting that developed in the late 1960s and 1970s as the complexity and interconnectivity of the world economy increased (Chermack, Lynham, & Ruona, 2001; Wack, 1985). With AM being considered a disruptive technology (Sealy, 2012), it matches well with the feature that "scenario planning forces organizational planners to consider paradigms that challenge current thinking" (Chermack et al., 2001, p.1). The ability to address uncertainty and develop an understanding of new technology integration makes scenario planning an ideal candidate for analyzing the impact of AM implementation.

Scenario Planning

Scenario planning began with the RAND corporation investigation of new weapons technology around World War II (Chermack et al., 2001), so the use of what was the "future-now" technique has its roots in the military, similar to supply chain and logistics. While there have been changes and innovations in different uses of scenario planning since inception (Chermack et al., 2001), Van der Heijden established five principles for scenarios (Van der Heijden, 2005):

- At least two but no more than four
- Plausible and reflecting current knowledge
- Internally consistent
- Relevant to the issue of concern
- New and original perspective to the issue of concern

Holmström et al. established two distinct approaches to AM implentation within spare parts supply chain, centralized or distributed deployment (Holmström et al., 2010), these scenarios are the logical ways AM would likely be configured for USAF deployed supply chain operations because the DoD already uses a centralized approach for logistics

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in the current contingency theater (Montero, 2007). Once scenarios are identified, traditional supply chain modeling with Monte Carlo simulation can be used to capture the expected differences between scenarios.

Monte Carlo Simulation

Monte Carlo Simulation is a technique from probability theory and sampling statistics that gained acceptance following World War II after use in Los Alamos and with the advent of the first electronic computer, the ENIAC (Metropolis & Ulam, 1949). This modeling technique allows users to combine variables defined by probability and ranges, rather than require specific knowledge of every possible outcome. The use of random sampling to refine estimates was used prior to the war by Enrico Fermi to surprise his colleagues, but he did not publish the method or use the name Monte Carlo (Metropolis, 1987). With the profusion of spreadsheet-based software in business, the method's application can be applied much quicker than building an elaborate model or full data collection of the true system (Hubbard, 2014).

Monte Carlo Simulation entails combining separate deterministic or stochastic variables, each with their own probabilities and distributions, into a combined single output variable in a randomly determined scenario. This process is then repeated for thousands to millions of trials until the single output variable shows enough fidelity to the output function curve (Hubbard, 2014). By using random numbers to generate each scenario, the iterative process populates varied points within each input variable's distribution parameters into a multi-dimensional, combinatorial output without knowledge of the precise functions governing the system being modeled (Metropolis & Ulam, 1949). Like all models, this process is not exact but is used to reduce the variance

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and uncertainty in understanding a system; as more information is discovered and applied, the variance reduction can be refined further, making the model useful in a tradeoff with the cost of additional information (Eckhardt, 1987; Hubbard, 2014).

Monte Carlo simulation is a proven method of modeling supply chain interactions and has been used to model supply chain risk, vendor selection, and cost effectiveness when uncertainties exist in the market demand or logistics (Deleris & Erhun, 2005; Jung, Blau, Pekny, Reklaitis, & Eversdyk, 2004; Schmitt & Singh, 2009; Wu & Olson, 2008; Zabawa & Mielczarek, 2003). This specific use of this method will be further expanded and applied in Chapter III of this research.

Summary

This chapter covers the review of literature which guided this research. It provides a definition and context for the importance of supply chain theory and logistics to the military. Then, the types of and steps used by all AM processes are given and, to tie together supply chain and AM research, recognized advantages of AM were categorized into supply chain goals of either efficiency or flexibility. This was followed by a brief review challenges to implementation and how they are being addressed. The primary costs and breakdown found from commonly used AM cost modeling techniques are introduced. Finally, a look at established research combining supply chain with AM gave a basis for a framework using scenarios and supply chain modeling techniques and lead to an introduction for scenario planning and Monte Carlo simulation.

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III. Methodology

Chapter Overview

This chapter presents the system definition and model created in this research to be used for a Monte Carlo simulation. First, the system is defined for the ECES locations within current contingency operations, then EOD bomb disposal robots are described as the equipment used for the basis of the model. The chapter then discusses the costs used for consideration in this research as compared with those of a pre-established framework to pave the way for the definition of scenarios to be considered in Chapter IV. Finally, data sources and cleanup are discussed before a detailed description of the model's dynamics is established.

System

To address the first investigative question for understanding how ECES repair part supply chain is currently used, the scope of this research was narrowed to a specific system for this research. The system definition is presented by the locations, the equipment, and the costs considered for the research and was created from a review of publicly available USAF and DoD websites, news articles, and repair data obtained from the Air Force Civil Engineer Center (AFCEC). This defined system was chosen to allow for an understanding of the current dynamics and repair part fulfillment. Then, the creation of a model populated with real world data is used as part of the third investigative question to compare how AM might impact the system. The model was created to best represent the desired and most likely scenarios for the research sponsor

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but included several assumptions that are noted in each of the system definition subsections.

Locations

AM deployment could mean a variety of things for the USAF due to its size: deployment for all world-wide operations, deployment for the US locations, or deployment for a specific theater. For this research, the system was defined as AM deployment to a combat theater, as represented by the current primary contingency area of responsibility (AOR), US Central Command (USCENTCOM), shown in Figure 1.

Figure 1: Map of USCENTCOM AOR (USCENTCOM, 2017)

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A combat theater was considered due to added challenges associated with contingency military supply chains and specifically USCENTCOM for its established ECES footprint. Since this research is considered for the squadron unit-level, assets were considered at the primary bases with stable ECES operations in the USCENTCOM AOR, shown in Figure 2: Al Udeid Air Base (AUAB), Al Dhafra Air Base (ADAB), Ali Al Salem Air Base (AAS), Bagram Airfield (BAF), and Kandahar Airfield (KAF).

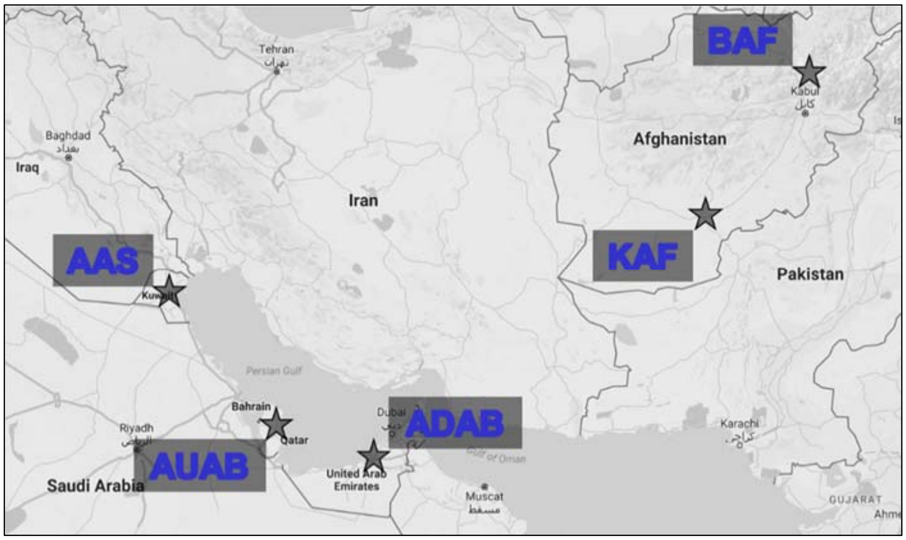

Figure 2: Primary Base Locations with ECES Support (AFCENT, 2017)

Equipment

As mentioned in Chapter I, EOD has been an early adopter of AM within CES units, so the use of AM for EOD operations was considered. Additionally, concurrent AFIT research is focused on the printing and testing of gears printed on AM machines from low to medium cost ranges for consideration of use on the newest USAF EOD robot acquisition, the Micro Tactical Ground Robot (MTGR) (Murphy, 2017). Repair data for USAF EOD use of the MTGR is limited, so the model developed uses available robot

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repair information for three other types of EOD bomb disposal robots used in similar ways: the iRobot SUGV 310, the iRobot Packbot 510, and the QinetiQ Talon series of robots. The Talon series robots could be further characterized by their specific loadout configuration of either Base, Mark 2 Mod 1, or IIIB, but were considered under the same Work Order (WO) type for this model because of the common architecture. These models have records of repair maintained by contract at the Joint Robotics Repair Facility at Tyndall AFB, FL and were assumed the only ones in use by ECES units for modeling purposes.

The three models of robots used in this research are primarily used by other branches but require USAF EOD personnel training for joint deployments. Because of this training requirement, there is a contract for the Joint Robotics Repair Facility to maintain a larger inventory of robots under one equipment manager than individual EOD flights. The contract ensures specific records of cost and work order information are kept consistently for repairs, which may not be as standardized or available between operational units. Additionally, these robot models have been utilized in USCENTCOM operations. The assumption was made that these robots are adequate to establish a basic model for this research.

EOD robotics repair in USCENTCOM is completed by the Joint Robotics Repair Detachment-Afghanistan (JRRD-A) based at BAF, which acts as a regional distribution center ran by US Army and Marine Corps personnel (Scar, 2011). The Army and Marines took the lead for unmanned ground vehicle (UGV) operations with a memorandum of understanding for the Robotic Systems Joint Project Office (RSJPO) formed in 1989 and has had thousands of systems in the USCENTCOM theater at a time

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(Kenyon, 2008). USAF EOD personnel deploy in relatively small teams and are assumed to have between three and five robots at an ECES location, resulting in only a fraction of the UGV systems in theater.

Costs

In their evaluation of AM for F-18 spare parts, Khajavi et al. accounted for eight annual costs: personnel, material, transportation, inventory carrying and obsolescence, aircraft downtime, AM investment, and initial inventory production (Khajavi et al., 2014). The current research does not have aircraft downtime directly associated with USAF EOD UGV operations and the JRRD-A aims to repair or provide a replacement unit within four hours due to criticality of mission demands (Scar, 2011). Literature indicates that labor costs are only a small component of AM part costs and that inventory related costs are *ill-defined* cost categories which are difficult to capture without explicit details that would only be available with known part designs and footprint required for the AM system (Thomas & Gilbert, 2014).

So, the repair personnel, carrying and obsolescence costs, and initial inventory production costs for the repair process are assumed to be relatively unchanged and primarily absorbed by the RSJPO due to the low percentage of USAF UGVs compared to the total UGVs in theater. The majority of the costs to the USAF of current operations are for parts and transportation to and from the JRRD-A, so these values would affect the decision whether or not to implement AM more than any others. For this reason, these are the primary costs accounted for in this research's model. These costs will be considered as the potential AM investment minimum value in the results and conclusions chapters of this research. If investment into an AM system, from designs to machine and

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material costs, is expected to be below the model's cost values then the purchase is justified; if the investment is expected to be higher, additional areas of cost would have to further explored.

Scenarios

Because parts are not currently produced through AM, there are two challenges to understanding the implication of AM for the EOD robots using this framework: the material requirements and likely designs of AM parts are unknown, and the AM system needed and associated cost are unknown. Each of these challenges is related to the effort of Shields' (2016) previous AFIT research into design development, which included a iterative design methodology and an EOD UGV attachment, and Murphy's (2017) concurrent AFIT research to test gears between AM machines with the intent to inform a specific end-use EOD UGV part. However, these are not the primary focus of this thesis effort. Rather this effort focuses on creating a model to estimate the annual intratheater transportation and part costs of current repairs.

These primary costs to the USAF can be understood as the minimum potential investment value or the amount a replacement system, AM or otherwise, would minimally be expected to be worth, i.e. if a system can operate for this value or less annually with other benefits that are harder to quantify it is worth using. The investment value can then be considered under the two challenging AM implementation configurations: *Centralized AM* vs. *Distributed AM*, and the two potential capability scenarios for each of *Fully Capable AM* and *Limited AM*. The scenarios are shown visually below in Figure 3: AM Scenarios Considered.

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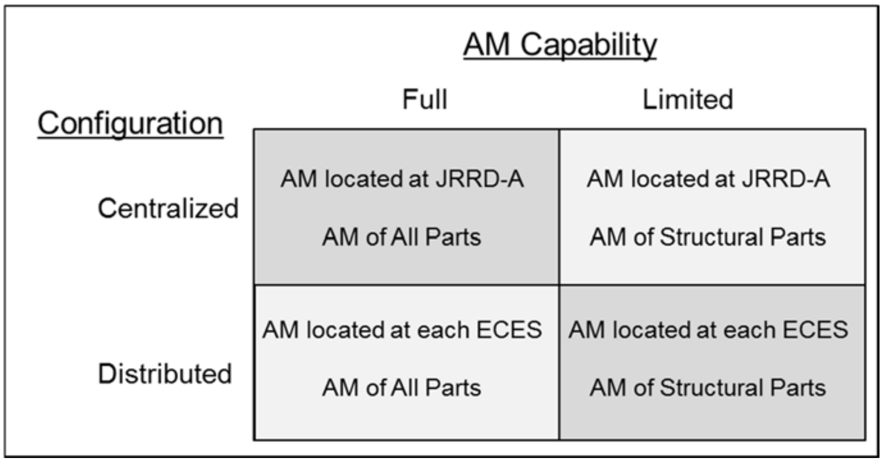

Configuration	AM Capability: Full	AM Capability: Limited
Centralized	AM located at JRRD-A AM of All Parts	AM located at JRRD-A AM of Structural Parts
Distributed	AM located at each ECES AM of All Parts	AM located at each ECES AM of Structural Parts

Figure 3: AM Scenarios Considered

Configuration

To answer the second investigative question, literature has already suggested that AM implementation will most likely consist of either a central AM location or distribution of AM to each point of maintenance (Holmström & Partanen, 2014; Holmström et al., 2010). The *Centralized AM* scenarios for this research assume that the JRRD-A location at BAF would continue to be the primary location for AM with the same shipping requirements as the traditional system. The *Distributed AM* scenarios assume AM would be implemented at the squadron level, so the scenarios use AM distributed to each ECES location presented above.

Capability

The *Fully Capable AM* repair scenarios assume the use of AM for all parts required in repairs. Though it would likely take multiple AM machines, there are current machines capable of producing everything from PC control boards and embedded electronics to wearable and reinforced cloth-like materials (Gao et al., 2015; Lipson &

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Kurman, 2013; Rayna & Striukova, 2014). The *Limited AM* repair scenarios assume the printing of only structural-type parts, and excludes the printing of cloth (ballistics covers and harnesses) or electronics (cameras, controllers, PC boards, antennae, and cables). The part costs for repairs used in the model for each WO were categorized go/no-go based on these capability limitations and the costs were tracked simultaneously but separately for consideration in a *Limited AM* scenario for each configuration.

Data

Transportation Costs

Transportation costs within theater were considered only by air due to the timely requirement for the return of UGVs to EOD units for safe operations. The rates for shipping were taken from the Air Mobility Command's published fiscal year 2017 (FY17) DoD Channel Passenger and Cargo Customer Billing Rates which provides tariff rates per pound based on the point of embarkation and point of debarkation zones. AUAB and ADAB are in Zone 9, AAS is in Zone 17, and BAF and KAF are in Zone 18; resulting in a consolidated table of cargo rates used, each given per pound and for cargo under 439 pounds, Table 5.

Table 5: Consolidated Cargo Rates with to and from the JRRD-A Highlighted

Base	Zone		To		
			9	17	18
AUAB ADAB	From	9	$ 3.82	$ 4.79	$ 5.59
AAS		17	$ 4.79	$ 6.38	$ 6.04
BAF (JRRD-A) KAF		18	$ 5.59	$ 6.04	$ 5.58

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To keep the model closer to the actual system dynamics, the shipping cost considered was taken from the point of use to the site of the JRRD-A, BAF, then from BAF back to the point of use. This was done under an assumption that if the specific robot sent to the JRRD-A was not repaired immediately, the same model type was sent back to the unit as a replacement.

Repair Data

Repair data was obtained from the Joint Robotics Repair Facility through the AFCEC. The data used to build the model was the complete WO repair list for the Tyndall based facility for FY16, which included extra information not used in this model such as Part Supplier, WO Technician, Failure site, etc. The columns used were WO number, part description, project (robot), and total cost with an added column for the go/no-go AM consideration and cost for this research. This spreadsheet was also limited to only rows containing repair WOs, eliminating quality assurance items, and subtotals were created for total cost of each WO. The full spreadsheet is available in APPENDIX A: Tyndall AFB Joint Robotics Repair Facility Data FY, with an example work order shown in Table 6:

Table 6: Sample WO Data Used for the Research Model

WONumber	Description	Project	Total Cost	AM Capable	AM Part Cost
FB48190000340	MPL-MF, GRIPPER FINGER BUMBER	MINI-EOD	$1.41	1	$1.41
FB48190000340	MPL-MF, ASSY,TRACK,FLIPPER,MINI-EOD	MINI-EOD	$96.46	1	$96.46
FB48190000340	MPL-MF, ASSY,TRACK,MAIN,MINI-EOD	MINI-EOD	$222.04	1	$222.04
FB48190000340	MPL-MF, BATTERY LATCH MECHANICAL ASSY	MINI-EOD	$1,337.48	1	$1,337.48
FB48190000340	MPL-MF, ASSY,CABLE,COMM-OCU,VUZIX13,GLN	MINI-EOD	$388.44	0	$0.00
FB48190000340 Total		**MINI-EOD**	**$2,045.83**		**$1,657.39**

Where the "AM Capable" column was given a 0 if it appeared to be either cloth or electronics for use in the *Limited AM* scenario and the individual part cost was then

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multiplied by this logic gate to get an "AM Part cost." In addition to the repair data shown, the total number of each robot system was given by the equipment manager and the percent of total units, total WOs by unit, and WO per unit were calculated (Table 7):

Table 7: Total Units and WOs for Each Robot System

System	Total	% of Total	WOs	WO/Unit
Mini-EOD Bot Sugv 310	43	47.25%	27	0.63
Packbot Fastac 510	25	27.47%	20	0.80
Talon Series	23	25.27%	26	1.13

The "WO/Unit" was used as the failure rate under the assumption that the systems under consideration follow the traditional Bathtub failure curve and have been in the DoD inventory long enough to reach the Intrinsic Failure Period, or a steady rate of failure, but not long enough to reach the exponentially increasing Wearout Failure Period (NIST/SEMATECH, 2017a).

Model

The model for this research was created in Microsoft Excel using standard inherent functions, the data analysis add-on, and a simple Microsoft Visual Basic for Applications (VBA) code to rerun and capture the model outputs multiple trials at a time. To begin modeling the USCENTCOM use of EOD UGVs by the USAF, the number and type of robots at each location was simulated through random number generation of a uniform distribution of either 3, 4, or 5 units per location with an assumption to follow the distribution of each type according to its percent of total inventory found in the Joint Robot Repair Facility's equipment list, given above in Table 7. The robot for each location and position number is found by using Equation 1.

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$$r_{i,j} = \begin{cases} 0, & x = 0 \\ 1, & 0 < x < .4725 \\ 2, & .4725 \leq x < .7473 \\ 3, & .7473 \leq x < 1 \end{cases} \qquad \textit{where } 0 \leq x < 1 \qquad (1)$$

Where, *r* returns the robot type for location *i* and robot position *j* based on the random number *x*. This resulted in a five by five table for the five locations and up to five robots at each. An example table is shown in Table 8, where a 1 is the SUGV 310, 2 is the Packbot 510, 3 is a Talon series robot, and 0 means that no robot occupies the 4th or 5th position.

Table 8: Sample Table of Robot Types Modeled for Each Location for One Trial

	Robot type				
	R1	R2	R3	R4	R5
AUAB	2	3	3	0	0
ADAB	2	1	2	2	0
AAS	1	1	1	2	0
BAF	3	3	2	3	2
KAF	1	1	3	1	0

Once the robot type was set for each trial, for each robot type a random number was created to determine if a break occurred at the failure rate given in Table 7 for WO per unit. The equation used to determine the cost of parts is given in Equation 2.

$$CP_{i,j} = \begin{cases} 0, & r_{i,j} = 0 \\ 0, & y \geq b(r_{i,j}) \\ p(r_{i,j}, z), & y < b(r_{i,j}) \end{cases} \qquad \textit{where } 0 \leq y < 1 \qquad (2)$$

Where random repair *z's* repair cost, *CP*, is pulled from a corresponding work order cost list, *p(r)*, if random number *y* is below the breakage rate, *b(r)*, for robot type *r*. For example, in the sample table given in Table 8, the first robot at AUAB is a type 2 (Packbot 510) so the random number to determine if a WO was required is evaluated against a less than or equal to comparison to the .80 WO per unit rate. If a WO is

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required, one of the 21 WOs for a Packbot is taken randomly from the repair list as the cost to repair the break. This assumed the repair lists for each type, given by the repair center, to be a discrete list of possible repair costs with several repairs being repeated in the list to account for common breaks, at least those seen in FY16. The total cost of work orders, total cost of AM able parts, and total cost of non-AM able parts is captured for the between zero and two WOs expected for robots in theater.

Once it is determined if a WO is required for one of the UGVs, a shipping cost is incurred for each WO from the rate table shown above in Table 5 at the weight of the given robot type, to and from BAF. The shipping cost is calculated by Equation 3:

$$CS_{i,j} = \begin{cases} 0, & CP_{i,j} = 0 \\ w(r_{i,j}) * t_i * 2, & CP_{i,j} > 0 \end{cases} \qquad (3)$$

Where the shipping cost, *CS*, for existing repairs is based on weight, *w(r)*, for robot type *r* at the tariff rate, *t*, for location *i* shipped to and from the JRRD-A. Additionally, the cost of parts that are considered for the limited AM capability are determined from the total WO cost, $CP_{i,j}$. Because the *CP*s are found from a discrete table for each WO cost, the cost for limited is found by a basic lookup from the WO cost table. If the cost of the limited AM is equal to the cost of the full WO, the shipping for the limited scenario is considered zero but is the normal rate otherwise. For each trial, the total annual shipping cost and total annual WO parts cost are captured as well as the potentially reduced total shipping cost of only non-AM able part WOs and the annual part costs for both AM able and non-AM able parts as shown in Table 9.

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Table 9: Sample Model Results for One Iteration

Scenario	Annual Cost	
Traditional System	Shipping	$7,295
	All Parts	$17,068
Traditional System with Limited AM	Shipping	$7,295
	AM Parts	$1,107
	Non-AM Parts	$15,961

Each annual cost was captured under the same demand circumstances to ensure the Monte Carlo Simulation used the same inputs across each of the scenarios considered for the research's evaluation of alternatives. The model executed 10,000 trials and reached a steady state for the cumulative average of each annual cost and for each an average value, five percent lower bound, and ninety-five percent upper bound were found. Additionally, a histogram of all trials was created for each cost to visually show the resulting distribution. The resulting annual costs, intervals, and histograms are presented and discussed in the next chapter.

To understand what the estimated annual costs imply for investment decisions for DoD acquisitions, the annual costs can be transformed into net present value (OMB, 2015; Wise & Cochran, 2006). To convert the annual costs into net present value, the present given an annuity formula, Equation 4, will be used (Eschenbach, 2011).

$$P = A * \frac{[(1+i)^N]}{[i*(1+i)^N]} \qquad (4)$$

Where *P* is the net present value, *A* is the annual cost, *i* is the real interest rate adjusted for inflation, and *N* is the number of years of annual costs. Circular A-94, Appendix C is the prescribed source for real interest rates to be used by federal agencies (OMB, 2015; Wise & Cochran, 2006).

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Investment into an AM system would be considered over the life of a machine, but the assumed expected life of AM machines has varied in research (Khajavi et al., 2014; Thomas & Gilbert, 2014). Additionally, Circular A-94, Appendix C gives rates for 3, 5, 7, and 10 years, which are .3%, .6%, .8%, and 1% respectively (OMB, 2015). This research will present net present values at each of these intervals to allow appropriate understanding of various AM machine life expectancy impacts.

Summary

This chapter introduced the system's locations and equipment considered for Monte Carlo simulation of costs associated with ECES EOD robot repair. The primary costs calculated are the transportation and part cost per work order. The chapter also introduced the scenarios and data used for the model. Finally, the interaction of inputs was described for the model's output. Chapter IV will discuss the results of this model.

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IV. Analysis and Results

Chapter Overview

This chapter presents the results of the model developed in this research to determine implications AM has on an ECES supply chain. The chapter presents the number of trials needed for the simulation, histograms of annual costs for each category considered, and interpretation of the expected costs for each scenario type: *Fully Capable AM* centralized at the JRRD-A, *Fully Capable AM* distributed to each ECES, *Limited AM* centralized at the JRRD-A, and *Limited AM* distributed at each ECES. The analysis of results returns an estimated minimum expected value for investment and an estimate for likely AM machine purchase cost which can contribute to acquisition strategy development for AM in USCENTCOM.

Model Results

The research model executed 10,000 trials and was stopped once it had been determined to reach a steady state for each average annual cost. Steady state for cost was defined as no more than a .05% fluctuation in the cumulative average annual cost found for at least one thousand straight trials. Steady state was reached for each cost according to Table 10:

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Table 10: Trials to Reach Steady State for Each Average Cost

Scenario	Annual Cost	Trials before steady state
Traditional System	Shipping	3143
	All Parts	4758
Traditional System with Limited AM	Shipping	3143
	AM Parts	7447
	Non-AM Parts	5182

The model was programed to perform one thousand trial iterations at a time using a VBA code to copy the values for each cost and add them to a list with each previous trial. Once the model reached steady state for the final cost, the *Limited AM* scenario's AM able part costs found at trial 7447 and determined as steady state after the 9000-trial point, the model was executed an extra round to ensure the steady state had been reached. Once confirmed, the cumulative averages, as well as the fifth and ninety-fifth percentiles were calculated, Table 11.

Table 11: Model Results for 10,000 Trials

Scenario	Annual Cost	Cumulative Average	5% Lower Bound	95% Upper Bound
Traditional System	Shipping	\$7,382	\$1,788	\$12,801
	All Parts	\$41,732	\$7,952	\$90,034
Traditional System with Limited AM	Shipping	\$7,101	\$1,788	\$12,800
	AM Parts	\$1,742	\$0	\$5,010
	Non-AM Parts	\$39,990	\$6,656	\$87,866

To better understand the intervals for each annual cost, a histogram was created for each set of values. Initially, to determine the bin size for each annual cost the range

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was divided by twenty-five and rounded to the tenth percentage decimal place, i.e. the hundreds for the shipping costs and the AM part cost vs. the thousands for the all part cost and the non-AM part cost. The first bin was found by adding a half bin size above the minimum cost from all trials. The histograms generated from these bin sizes resulted in every other bin and higher cost bins being empty or near-empty. New histograms were created by doubling the bin sizes and reducing the number of bins used from twenty-five to ten. Reduced size histograms are shown in Figure 4 and Figure 5 to compare shapes, but full size figures are available in Appendix B.

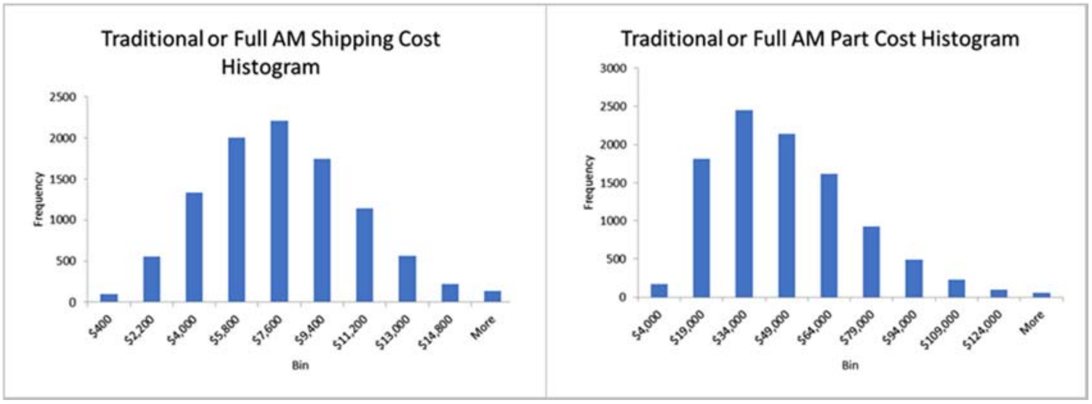

Figure 4: Traditional or Full AM Annual Cost Histograms

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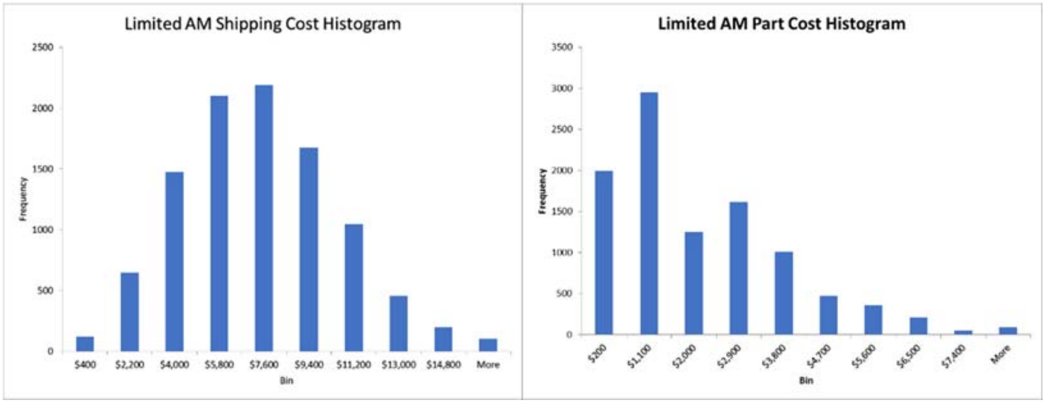

Figure 5: *Limited AM* Scenario Annual Cost Histograms

Shown in the shape of the histograms, the shipping costs behave in a relatively symmetric way, similar to a normal distribution, with the mean and median being less than 5% different from each other. Whereas, the part costs have a distinct right skewness for their histograms and greater than 10% difference between the mean and medians; therefore, it is important to note the medians for these costs (NIST/SEMATECH, 2017b), see Table 12.

Table 12: Median Annual Part Costs

Scenario	Annual Cost (Median)	
Traditional System	All Parts	$37,837.00
Traditional System with Limited AM	AM Parts	$ 1,107.00
	Non-AM Parts	$36,107.50

For each type of part cost, the median is smaller than the mean, or average, so the median will be conservatively used as the expected cost instead of the mean.

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Interpreting the model

As noted in Chapter III, two important aspects for understanding the basic cost of AM implementation are: what are the details of the parts to be created with AM and what are the AM machine details. Since the specific details for each are unknown for this research and the three UGVs modeled are not commonly used by USAF EOD units, the results must be interpreted in general terms of the potential annual investment value for an AM system to replace the current repair process, either in centralized or distributed configuration.

As discussed in Chapter II, the total cost of AM depends on factors such as building rate, utilization rate, material costs, or machine purchase cost. And, the primary cost factor has proven to be initial machine purchase cost which has been repeatedly shown to be a relatively consistent range when given as a proportion of the overall cost per-part. The average of 65% of the total cost per part, taken from sensitivity analysis of the cost factors by Lindemann et al. (2012), matches other estimates for metal and plastic AM part cost estimates and will be used for this research to provide guidance for an appropriate machine purchase cost.

Traditional repair parts and the raw AM material of the corresponding replacement part should be of similar weight, and is assumed to not significantly change the cost of shipping to USCENTCOM between the traditional system and the scenarios. This research also assumes there is no discounted value of purchasing multiple machines or other significant differences for machines at one vs. all locations. Finally, it is expected that the cargo shipping rates will not substantially change over the life of AM machines.

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Fully Capable AM Scenario

The potential value of investment to replace current repair operations under a *Fully Capable AM* scenario within USCENTCOM is expected to be worthwhile for an approximate annualized cost of $37,800 for parts. The replacement of EOD's bomb disposal robot repair system for the types of robots used in this model would likely require an integrated AM system with multiple machines and materials. This value is only for the WO costs and therefore only represents one system at the JRRD-A, whereas if systems were distributed to each ECES location in the model, there would be added value from eliminating intratheater shipping and would be worth an expected $7,380 more. Therefore, an expected total investment value would be $9,000 per site annually once the combined part and shipping costs are divided between the five ECESs.

Consequently, investment into an AM system over its life in net present value should be at least worth between $112,700 and $358,000 for implementing AM at BAF or between $26,800 and $85,000 for placing AM at each ECES location. Table 13 shows each expected life's estimated present value.

Table 13: Lifetime Investment Values for Full AM Capability Scenarios

Full AM Capability Scenarios		
Machine Life	**Centalized (BAF)**	**Distributed (each ECES)**
3-year	$112,000	$26,000
5-year	$185,000	$44,000
7-year	$256,000	$61,000
10-year	$358,000	$85,000

Applying the 65% estimation to understand a rough approximation of what these values mean in terms of machine purchase cost would mean that the expected machine purchase

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costs could reasonably be expected between $72,800-$232,700 or $16,900-$55,250 for each configuration, respectively.

Limited AM Scenario

If, however, the more likely acquisition were pursued for smaller AM systems with capability limited to the non-electronic and non-cloth portions of UGVs, then the expected investment to replace the ECES portion of the repairs at the JRRD-A would be expected to be worth $1,100 per year for parts with the added value of distributing systems only expected to decrease cost by an additional $280 per year, resulting in $275 investment per site.

This means that the total investment into an AM system within USCENTCOM for USAF EOD UGV repair over its life should be at least between $3,200 and $10,400 at the JRRD-A or $800 to $2,600 at each ECES unit. Each expected life's estimated present value is shown in Table 14.

Table 14: Lifetime Investment Values for Limited AM Capability Scenarios

Limited AM Capability Scenarios		
Machine Life	**Centalized (BAF)**	**Distributed (each ECES)**
3-year	$3,200	$800
5-year	$5,400	$1,300
7-year	$7,400	$1,800
10-year	$10,400	$2,600

Applying the machine purchase cost estimate calculation of 65% of total cost to get a rough understanding of what this means for machine acquisition provides estimates of $2,080-$6,760, at BAF or $520-$1,690 per ECES site.

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Summary

This chapter presented the model results for shipping and part costs associated with USAF EOD robot repair supply chains within a combat theater. The results included the number of trials needed for the simulation, histograms of each annual cost considered, and interpretation for each scenario type: *Fully Capable AM* at the JRRD-A, *Fully Capable AM* distributed to each ECES, *Limited AM* at the JRRD-A, and *Limited AM* at each site. The analysis of results focused on the expected value of investment for replacing the current repair process's parts and intratheater airlift costs, as viewed with the potential for AM as a replacement. This value for the JRRD-A, or each ECES location, was transformed into the likely machine purchase value to help inform an acquisition strategy for AM in USCENTCOM for the system defined by this research.

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V. Conclusions and Recommendations

Chapter Overview

This chapter uses the results of the methodology and model to circle back and answer the investigative questions introduced in Chapter I. The conclusions drawn from the research and the research's significance are discussed. Finally, recommendations for action and future research areas are highlighted before concluding the research.

Investigative Questions Revisited

The primary purpose of this research was to investigate the effects of AM on ECES supply chains and provide information for better decisions in AM application. The ultimate goal was to create a flexible decision tool for deployed operations managers to determine whether AM should be integrated with other supply chain fulfillment methods. To meet the research's purpose, three primary investigative questions were explored and analyzed as follows:

1. *How can Expeditionary Civil Engineer Squadrons define current supply chain fulfillment methods?*

This question was meant to explore how a system used in an ECES supply chain could be defined, with the hypothesis that a system could be defined and modeled based on current contingency theater dynamics. By focusing in on a specific process, in this case the repairing of EOD robots within USCENTCOM, it was possible to define the primary aspects of the system through a review of available literature guided by keywords found in general research into EOD and military logistics areas.

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The use of keywords enabled the discovery of published DoD news articles and transportation rates and rules. The remaining system definition was found through a detailed search of publicly facing DoD websites for units in the USCENTCOM AOR. The resulting aggregation enabled creation of a realistic ECES supply chain that, while not fully representative of all ECES supply chain fulfillment methods, could be used as a basis for a modeling framework.

2. *How would Expeditionary Civil Engineer Squadrons most likely implement AM in a contingency operation theater?*

This question was meant to explore how AM should be configured within a contingency theater in terms of distribution of AM machine locations based on available research. In the review of available research into the cross between AM and supply chain, it was found that a framework providing guidance to AM site configuration was already established and offered a basis to define this research's scenario types.

The framework used presented one configuration scenario using a regional distribution center, which matched the hub-and-spoke system already seen in expeditionary theater; while the other configuration scenario takes full advantage of AM's potential for increased flexibility through distribution to each end-use location (Holmström et al., 2010).

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3. *How would an AM-enhanced supply chain fulfillment compare to current supply chain fulfillment for Expeditionary Civil Engineer Squadrons?*

This question was meant to explore the differences between a current supply chain activity as compared to the same activity if realized through AM, with the hypothesis that these can be compared using an established supply chain modeling technique. It was found that a model based on the system definition could use established Monte Carlo simulation to understand cost of the repair parts and transportation to and from a repair depot at BAF. These costs were then used as an indication of the amount that would be worth spending on an improved version of the repair part system, meaning AM for this research. In a centralized AM configuration, the annual values can be considered as a baseline for understanding AM implementation decisions were $1,100 per year for *Limited AM* capability or $37,800 per year for *Fully Capable AM* replacement of repair parts. Likewise, for distributed AM, the expected annual value of *Limited AM* and *Full AM* are $275 and $9,000.

Using relatively consistent rates found in existing research indicating the proportional amount that machine purchase costs contribute to overall production costs, it can be expected that machine purchase costs will be approximately 65% of the cumulative investment value over the machines life. This means that initial machine costs that could reasonably be expected are $72,800 to $232,700 for a JRRD-A *Fully Capable AM* machines, $16,900 to $55,250 for distributed *Fully Capable AM* machines, $2,080 to $6,760 for a JRRD-A *Limited AM* machines, or $520 to $1,690 for distributed *Limited AM* machines.

However, not all AM cost areas used in previous literature were able to be fully captured because of the lack of a detailed part designs for cost analysis. This design ambiguity limitation accentuated the challenge of capturing costs because there is still the

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variability of finding an appropriate AM solution, which includes a diverse range of options for processes and materials with unique pros and cons and costs associated. Additionally, defining some of the complex ill-structured cost categories for supply chains, such as inventory costs, proximity to production costs, or vulnerability to disruption costs, is difficult for the theoretical nature of the research model's system.

Conclusions of Research

Applying the methodology of this research and reviewing the subsequent results of the model created had two primary takeaways. First, in defining the system for the research, an unexpected supply chain dynamic was seen with the equipment type selected. Despite this, the research direction was maintained because of the perception of higher potential for implementation based on existing related research efforts. Second, even in a restricted definition of repair parts and in not using a specific AM system, a useful framework was established to understand primary basic costs that could inform a decision-maker of the value at which AM can be considered for a current supply system.

The system in the research was defined primarily from the type of equipment for consideration, EOD bomb disposal robots, and geographical locations, USCENTCOM ECES sites. But, an unexpected aspect of the system was found in the uniqueness of the process dynamics in comparison to the expected repair supply chain options. The in-theater repair depot located at Bagram Air Field, Afghanistan, and the fact that it is primarily supported by US Army and Marine personnel, resulted in the research model not falling into the expected types of repair supply chains anticipated at the start of the research. By having the depot within theater, the implications of AM were more focused

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exclusively within the combat theater's smaller geographic context and had less emphasis on the time savings generally associated with AM.

The usefulness of the research model is enhanced because of the equipment opted for in the research, even with the unexpected dynamics introduced. The early adoption of AM by the EOD career field shows the potential for more immediate support of AM and the criticality of EOD robots for dangerous missions enhances their priority for air transit, reducing the conveyance methods which had to be considered for the model, thus helping establish an initial but realistic framework. The equipment criticality also had the added benefit of a subsequent requirement for detailed equipment tracking, which led to the ability to find Stable Failure Rates from existing USAF EOD repair data from a joint robotics repair facility.

Though not all costs were able to be captured by the research model, the primary costs of shipping and parts are informative for potential AM implementation as the largest portion of costs that could be replaced through AM investment. In his research of AM use on EOD UGV gears, Murphy (2017) found that a $2,500 AM machine demonstrated greater gear tooth bending strength but lower overall quality than a higher priced machine from a different process category. At this price, the low-cost machine is under the total estimated investment value of each scenario found from the Monte Carlo model when using a ten-year life.

Though this price is higher than the rough 65% estimate for an AM machine cost within the lowest value scenario of *Limited AM* in distributed configuration, estimated to be $1,690 per site for 10 year machine life; a price of $2,500 would be approximately 96% of the 10-year investment savings of this scenario, which is not far from the fraction

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of the cost per part to be accounted for from the machine purchase cost in some AM research into end-use metal parts but not polymer parts (Atzeni & Salmi, 2012). Further, the emphasized benefits of AM, as explored in Chapter II, are the increased flexibility and efficiency that may be seen on the *ill-defined* cost side of the total supply chain cost, which may be weighted higher for the deployed environment and is dependent on the person making the decision. While this investment would be higher than ratio's expected value, once an operations manager includes any of the *ill-defined* benefits, these could outweigh the cost difference for one or all sites. Thus, a reasonable decision for an expeditionary operations manager could be to pursue distributed configuration with the $2,500 AM machine, and this methodology helped capture some of the largest cost inputs to the decision without defining specific part designs.

The results of the research suggest the methodology used may be worth exploring in an expanded version of the system found, such as including the forthcoming breakage information, WO costs, and weight for the MTGR robot system; or including the additional value from expanding to the joint inventory of robots used by each branch and serviced by the JRRD-A to include their locations. Further, the methodology can be expanded to additional system definitions and dynamics by starting from the beginning of the methodology by defining the system from the ground up, using available literature and applicable shipping rates to understand primary costs, then applying a similar capability filter between *Fully Capable AM* and *Limited AM* to estimate AM investment values.

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Research Limitations

A limitation in this research is the lack of current widespread use of AM by most CES career fields. There is some use within the EOD community but this technology is still in early stages of use and understanding (Alwabel et al., n.p.; Shields, 2016). EOD has a specific and unique mission set, but the principles applied to EOD should be generalizable to additional CES functions. Therefore, this research will focus on an EOD application with the expectation of expansion of the developed methodology to additional areas.

The specific area of EOD selected to model is the repair of bomb disposal robots that are used in a deployed environment. However, the most recent model of robot has not been fully fielded from the initial acquisition order (Opall-Rome, 2015), and therefore is relatively untested in the field and repair requirements unexplored in USAF operations. This additional limitation is addressed by the assumption that the research model can be developed for other models of EOD robots which have been used throughout the current contingency theater. Though the specific units selected are primarily used by other DoD branches, the insight into the model is still expected to be useful for understanding AM implication.

Another important assumption is that an appropriate option exists for manufacturing required for replacement parts. This assumption is based on the variety of AM systems and capabilities available (DoE, 2015; Gao et al., 2015; GAO, 2015b). AM's diverse subdivisions, each with pros and cons, could alone be full research efforts. This research will assume that an acquisition proposal would select an effective AM technology, or combination of technologies, appropriate for this application. The goal of this research is to provide meaningful input to the process.

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Significance of Research

The creation of this research's methodology attempted to incorporate flexibility for modeling by starting from the basic system definition and dynamics development, then using a simple filter for AM capability to understand potential scenario differences in primary cost categories of part cost and appropriate shipping cost. The intent was to take this research in concert with efforts into AM capability topics in a related sample area of ECESs, i.e. EOD robots, and to inform decision making for AM implementation in an expeditionary environment based on expected investment value baseline found from the primary cost factors seen in the traditional system.

Ultimately, the overall research goal was for generalizability of the methodology to additional areas of ECESs (or other USAF units) with more diverse supply chain fulfillment in order to have a wider impact across the USAF. Based on this initial application of the methodology, this should be possible as long as the system can be properly defined in terms of locations, shipping rates, and repair part costs. These factors were taken in this research from a theoretical system designed to closely follow an existing system's repair supply chain in order to establish the methodology framework which can eventually be used to incorporate shipping and part cost consideration into real-world AM implementation and acquisition decisions.

The model created was intended as a theoretical initial step toward advising AM implementation for CESs or ECESs. But, the reliance of other branches on the joint repair depot and the interoperability of EOD units across DoD branches enhanced the potential impact of the theoretical research model. Because of the other branches' UGVs represented in the model and the much larger number of UGVs utilized by the other

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military branches, there could be added value from the research effort beyond USAF EOD units. Further, while this system may not be fully representative of other CES or ECES supply chains, the process of defining and applying Monte Carlo simulation to model a CES or ECES supply chain was successful and should be used to inform implementation decisions.

Recommendations for Action

Literature offered guidance for general, governmental, and DoD-specific AM implementation and should be used as a starting point for moving forward with acquisition of part designs or systems with specific applications in mind. The model showed relatively modest potential values of investment into AM for repair parts within a combat theater in comparison to a major branch-wide DoD acquisition contract, such as the $25 million USAF contract for the MTGR (Opall-Rome, 2015). If a portion of the initial acquisition included provisions for technical data, the design investment could be covered as a small portion of this large contract instead of as a standalone effort or with later procurement of AM machines, and this would eliminate some concerns with intellectual property.

With the limited demand observed in the system modeled, the value of AM could be higher if the DoD followed the GAO recommendation for military-wide tracking of AM applications and overlap of effort. Acting as a logistics provider has been suggested as the most advantageous position within an integrated AM supply chain. Inter-service cooperation could lead to a better AM posture through higher AM utilization rates because of increased numbers of end-users rather than narrowly focusing only on the

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lowest level application with a reduced machine use. The US military is such a large organization, with large sub-organizations, that it is in a prime position to take advantage of AM. Joint AM benefits are especially possible in a combat theater where multiple services are collocated at a common base, as with the JRRD-A at BAF. But again, increased cooperation is needed for acquisition efforts that obtain a cross-capable AM machine so that the role of logistics provider can be achieved for multiple end-uses.

Recommendations for Future Research

This research was intended to develop a methodology that leveraged existing modeling and AM frameworks presented in literature. The amount of potential, and questions remaining, for AM means that directions for future research are abundant. Some possible directions related to this research could include:

- Apply methodology to more ECES items or areas
- Apply methodology with the addition of low/med/high demand filter
- Expand model to all USAF CESs, to additional military branches, or to include more supply chain components
- Analyze an AM machine's robustness for varied part types
- Analyze AM investment value for obsolete repair parts
- Analyze appropriate organizational level to lead AM
- Analyze training requirements for AM implementation

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Conclusion

AM is a technology which should be considered for integration into supply chain fulfillment for Expeditionary Civil Engineer operations. The primary basic costs found in AM literature are machine purchase cost followed by material cost, and can be estimated by finding traditional fulfillment model costs using Monte Carlo simulation. In looking into basic cost factors' traditional fulfillment equivalents, a baseline value of investment into AM systems can be estimated and contribute information for decision making on AM implementation in variations of AM configuration strategy.

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APPENDIX A: Tyndall AFB Joint Robotics Repair Facility Data FY16

WONumber	Description	Project	Total Cost	AM Capable	AM Part Cost
FB48190000279	MPL-MF, MANIP,TURRET,CAM RNG FINDER(MINI-EOD)	MINI-EOD	$24,962.18	0	$0.00
FB48190000279 Total		**MINI-EOD**	**$24,962.18**		**$0.00**
FB48190000280	MPL-MF, BATTERY LATCH MECHANICAL ASSY	MINI-EOD	$668.74	1	$668.74
FB48190000280 Total		**MINI-EOD**	**$668.74**		**$668.74**
FB48190000281	MPL-MF, MANIP,TURRET,CAM RNG FINDER(MINI-EOD)	MINI-EOD	$24,962.18	0	$0.00
FB48190000281 Total		**MINI-EOD**	**$24,962.18**		**$0.00**
FB48190000282	MPL - PC BOARD, DAUGHTER, IIIB (WILL REPLACE PART NUMBER DSI-500-0517) ORDER DSI-500-0517 UNTIL OBSOLESCES	TALON	$1,245.00	0	$0.00
FB48190000282	MPL - PCB, MOTION CONTROL, AMC	TALON	$4,292.00	0	$0.00
FB48190000282 Total		**TALON**	**$5,537.00**		**$0.00**
FB48190000283	MPL - CAMERA ASSEMBLY, INFRARED ILLUMINATED, COLO	TALON ENGINEER	$1,448.00	0	$0.00
FB48190000283	MPL - RETENTION PIN, WHEELS AND CAMERAS (92384A013)	TALON ENGINEER	$40.00	1	$40.00
FB48190000283 Total		**TALON ENGINEER**	**$1,488.00**		**$40.00**
FB48190000302	MPL - MANIFOLD, E-BOX	TALON ENGINEER	$3,460.00	0	$0.00
FB48190000302	MPL - HARNESS ASSEMBLY, LOWER (BASE) ARM (MUST BE ORDERED BY REV. LEVEL)	TALON ENGINEER	$1,372.00	0	$0.00
FB48190000302 Total		**TALON ENGINEER**	**$4,832.00**		**$0.00**
FB48190000303	MPL-MF, BATTERY LATCH BAR	MINI-EOD	$24.00	1	$24.00
FB48190000303	MPL-MF, BATTERY LATCH MECHANICAL ASSY	MINI-EOD	$668.74	1	$668.74
FB48190000303 Total		**MINI-EOD**	**$692.74**		**$692.74**
FB48190000304	MPL-F, ASSY,ANTENNA,4.9 GHZ,RCV (USED ON BOTH THE FASTAC AND THE MINI-EOD)	MINI-EOD	$365.65	0	$0.00
FB48190000304	MPL-MF, CAMERA MOUNT PIVOT (USED WITH 91770A147)	MINI-EOD	$18.72	1	$18.72
FB48190000304	OGB-MF, 18-8 STAINLESS STEEL TRUSS HEAD PHILLIPS MACHINE SCREW,6-32 THREAD 7/16" LENGTH(USED WITH 4213563 & FRONT 4-BAR)	MINI-EOD	$0.05	1	$0.05
FB48190000304 Total		**MINI-EOD**	**$384.42**		**$18.77**

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WONumber	Description	Project	Total Cost	AM Capable	AM Part Cost
FB48190000316	MPL-MF, ASSY,CABLE,COMM-OCU,VUZIX13,GLN	MINI-EOD	$388.44	0	$0.00
FB48190000316 Total		**MINI-EOD**	**$388.44**		**$0.00**
FB48190000317	ASSY,GRIPPER CARTRIDGE,PACKBOT FASTAC (NEW PART# 4254670)	PACKBOT FASTAC	$5,800.00	1	$5,800.00
FB48190000317	MPL-F, ASSY,GAMEPAD,USB,PACKBOT 510	PACKBOT FASTAC	$81.00	0	$0.00
FB48190000317	AMREL AC ADAPTER	PACKBOT FASTAC	$141.20	0	$0.00
FB48190000317 Total		**PACKBOT FASTAC**	**$6,022.20**		**$5,800.00**
FB48190000320	MPL - PC BOARD, COMMS, VIDEO MATRIX (SPECIFY FOR WHICH VEHICLE GENERATION-- IIA OR III)	TALON	$1,894.00	0	$0.00
FB48190000320 Total		**TALON**	**$1,894.00**		**$0.00**
FB48190000322	MPL-F, BATTERY, LITHIUM,RECHARGEABLE,11.1V,7200 MAH-AMREL LAPTOPS	PACKBOT FASTAC	$385.00	0	$0.00
FB48190000322 Total		**PACKBOT FASTAC**	**$385.00**		**$0.00**
FB48190000323	MPL-F OCU,15IN,ASSY-AMREL RK886 W/ HARDWARE(CONT. PN 4181900)	PACKBOT FASTAC	$13,121.46	0	$0.00
FB48190000323 Total		**PACKBOT FASTAC**	**$13,121.46**		**$0.00**
FB48190000324	MPL-MF, CAMERA MOUNT PIVOT (USED WITH 91770A147)	MINI-EOD	$18.72	1	$18.72
FB48190000324	OGB-MF, 18-8 STAINLESS STEEL TRUSS HEAD PHILLIPS MACHINE SCREW,6-32 THREAD 7/16" LENGTH(USED WITH 4213563 & FRONT 4-BAR)	MINI-EOD	$0.05	1	$0.05
FB48190000324 Total		**MINI-EOD**	**$18.77**		**$18.77**
FB48190000325	MPL - KIT, ANTENNA, VIDEO, COFDM (4.4-5.0 GHZ)(BOXED DSI-500-1069)	MTRS TALON MK2	$1,530.00	0	$0.00
FB48190000325 Total		**MTRS TALON MK2**	**$1,530.00**		**$0.00**
FB48190000327	MPL-F, ASSY,ADJUSTABLE GRIPPER,RIGHT,PACKBOT FASTAC	PACKBOT FASTAC	$244.00	1	$244.00
FB48190000327	MPL-F, ASSY,ADJUSTABLE GRIPPER,LEFT,PACKBOT FASTAC	PACKBOT FASTAC	$244.00	1	$244.00
FB48190000327 Total		**PACKBOT FASTAC**	**$488.00**		**$488.00**

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WONumber	Description	Project	Total Cost	AM Capable	AM Part Cost
FB48190000328	MPL-F, BATTERY, LITHIUM,RECHARGEABLE,11.1V,7200 MAH-AMREL LAPTOPS	PACKBOT FASTAC	$385.00	0	$0.00
FB48190000328 Total		**PACKBOT FASTAC**	**$385.00**		**$0.00**
FB48190000330	MPL-F, ASSY,HANDLE STRAP,CHASSIS,PACKBOT FASTAC	PACKBOT FASTAC	$166.25	1	$166.25
FB48190000330 Total		**PACKBOT FASTAC**	**$166.25**		**$166.25**
FB48190000335	XBOX 360 WIRED USB CONTROLLER	MINI-EOD	$46.99	0	$0.00
FB48190000335	OGB-MF, TAC-EYE LT - IROBOT SYSTEM	MINI-EOD	$2,250.00	0	$0.00
FB48190000335 Total		**MINI-EOD**	**$2,296.99**		**$0.00**
FB48190000340	MPL-MF, GRIPPER FINGER BUMBER,(USED WITH MINI-EOD,FASTAC,PACKBOT)	MINI-EOD	$1.41	1	$1.41
FB48190000340	MPL-MF, ASSY,TRACK,FLIPPER,MINI-EOD	MINI-EOD	$96.46	1	$96.46
FB48190000340	MPL-MF, ASSY,TRACK,MAIN,MINI-EOD	MINI-EOD	$222.04	1	$222.04
FB48190000340	MPL-MF, BATTERY LATCH MECHANICAL ASSY	MINI-EOD	$1,337.48	1	$1,337.48
FB48190000340	MPL-MF, ASSY,CABLE,COMM-OCU,VUZIX13,GLN	MINI-EOD	$388.44	0	$0.00
FB48190000340 Total		**MINI-EOD**	**$2,045.83**		**$1,657.39**
FB48190000341	MPL-MF, BATTERY LATCH MECHANICAL ASSY	MINI-EOD	$668.74	1	$668.74
FB48190000341 Total		**MINI-EOD**	**$668.74**		**$668.74**
FB48190000348	MPL-MF, COMPUTER,RUGGED-THERMITE(MINI-EOD)	MINI-EOD	$9,336.80	0	$0.00
FB48190000348 Total		**MINI-EOD**	**$9,336.80**		**$0.00**
FB48190000349	MPL - PC BOARD, POWER DISTRIBUTION E-BOX ///REPLAC	TALON ENGINEER	$581.00	0	$0.00
FB48190000349	MPL ARMSUBASSEMBLY TALONIIIB W/CABLES W/O GRIPPER WRIST CAMERAS	TALON ENGINEER	$19,543.00	0	$0.00
FB48190000349	MPL - MANIFOLD, E-BOX	TALON ENGINEER	$3,460.00	0	$0.00
FB48190000349	MPL - E-BOX STACK	TALON ENGINEER	$7,973.00	0	$0.00
FB48190000349	MPL - CAMERA ASSEMBLY, MODIFIED	TALON ENGINEER	$1,393.00	0	$0.00
FB48190000349	MPL - HARNESS ASSEMBLY, AMC PHASE (RED, WHITE, BLUE)	TALON ENGINEER	$434.00	0	$0.00
FB48190000349 Total		**TALON ENGINEER**	**$33,384.00**		**$0.00**
FB48190000355	MPL-MF, MANIP,TURRET,CAM RNG FINDER(MINI-EOD)	MINI-EOD	$24,962.18	0	$0.00
FB48190000355 Total		**MINI-EOD**	**$24,962.18**		**$0.00**

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WONumber	Description	Project	Total Cost	AM Capable	AM Part Cost
FB48190000356	MPL - L PANEL ASSEMBLY, (POPULATED AND WIRED) (WITH SWITCHES AND HARNESSES)	TALON ENGINEER	$3,509.00	0	$0.00
FB48190000356 Total		**TALON ENGINEER**	**$3,509.00**		**$0.00**
FB48190000359	XBOX 360 WIRED USB CONTROLLER	MINI-EOD	$46.99	0	$0.00
FB48190000359 Total		**MINI-EOD**	**$46.99**		**$0.00**
FB48190000368	MPL-F, ASSY,ANTENNA,4.9 GHZ,RCV (USED ON BOTH THE FASTAC AND THE MINI-EOD)	MINI-EOD	$365.65	0	$0.00
FB48190000368	MPL-MF, DISPLAY,HEAD MOUNTED,GLASSES	MINI-EOD	$3,045.64	0	$0.00
FB48190000368	MPL-MF, CAMERA MOUNT PIVOT (USED WITH 91770A147)	MINI-EOD	$18.72	1	$18.72
FB48190000368	OGB-MF, 18-8 STAINLESS STEEL TRUSS HEAD PHILLIPS MA	MINI-EOD	$0.05	1	$0.05
FB48190000368 Total		**MINI-EOD**	**$3,430.06**		**$18.77**
FB48190000375	OGB-MF, TAC-EYE LT - IROBOT SYSTEM	MINI-EOD	$2,250.00	0	$0.00
FB48190000375	MPL-MF, CHASSIS RADIO ASSEMBLY(MINI-EOD/XM1216 WITH TETHER)	MINI-EOD	$2,554.35	1	$2,554.35
FB48190000375	MPL-MF, ASSY,CABLE,COMM-OCU,VUZIX13,GLN	MINI-EOD	$388.44	0	$0.00
FB48190000375	MPL-MF, OCU RADIO CONTROLLER(MINI-EOD)	MINI-EOD	$2,764.06	0	$0.00
FB48190000375	MPL-MF, COMPUTER,RUGGED-THERMITE(MINI-EOD)	MINI-EOD	$9,336.80	0	$0.00
FB48190000375 Total		**MINI-EOD**	**$17,293.65**		**$2,554.35**
FB48190000377	MPL-MF, GRIPPER FINGER BUMBER,(USED WITH MINI-EOD,FASTAC,PACKBOT)	MINI-EOD	$0.94	1	$0.94
FB48190000377 Total		**MINI-EOD**	**$0.94**		**$0.94**
FB48190000380	MPL-F, ASSY,ANTENNA,4.9 GHZ,RCV (USED ON BOTH THE FASTAC AND THE MINI-EOD)	MINI-EOD	$365.65	0	$0.00
FB48190000380 Total		**MINI-EOD**	**$365.65**		**$0.00**
FB48190000383	MPL-F, ASSY,ANTENNA,4.9 GHZ,RCV (USED ON BOTH THE FASTAC AND THE MINI-EOD)	MINI-EOD	$365.65	0	$0.00
FB48190000383	MPL-MF, MANIP,TURRET,CAM RNG FINDER(MINI-EOD)	MINI-EOD	$24,962.18	0	$0.00
FB48190000383 Total		**MINI-EOD**	**$25,327.83**		**$0.00**
FB48190000394	MPL-F, ASSY,GAMEPAD,USB,PACKBOT 510	PACKBOT FASTAC	$81.00	0	$0.00
FB48190000394 Total		**PACKBOT FASTAC**	**$81.00**		**$0.00**

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WONumber	Description	Project	Total Cost	AM Capable	AM Part Cost
FB48190000395	MPL - E-BOX STACK	TALON 3B EOD	$7,973.00	0	$0.00
FB48190000395 Total		**TALON 3B EOD**	**$7,973.00**		**$0.00**
FB48190000396	MPL-F, BATTERY, LITHIUM,RECHARGEABLE,11.1V,7200 MAH-AMREL LAPTOPS	PACKBOT FASTAC	$385.00	0	$0.00
FB48190000396 Total		**PACKBOT FASTAC**	**$385.00**		**$0.00**
FB48190000397	MPL-F, ASSY,ANTENNA,4.9 GHZ,RCV (USED ON BOTH THE FASTAC AND THE MINI-EOD)	MINI-EOD	$365.65	0	$0.00
FB48190000397 Total		**MINI-EOD**	**$365.65**		**$0.00**
FB48190000398	MPL - CAMERA ASSEMBLY, INFRARED ILLUMINATED, COLOR VIDEO (WITHOUT BRACKETRY & CONNECTOR)	TALON ENGINEER	$916.00	0	$0.00
FB48190000398	MPL - KIT, ANTENNA, VIDEO, COFDM (4.4-5.0 GHZ)(BOXED D	TALON ENGINEER	$1,530.00	0	$0.00
FB48190000398	MPL - PC BOARD, COMMS, VIDEO MATRIX (SPECIFY FOR WHICH VEHICLE GENERATION-- IIA OR III)	TALON ENGINEER	$1,894.00	0	$0.00
FB48190000398 Total		**TALON ENGINEER**	**$4,340.00**		**$0.00**
FB48190000399	MOTOR ASSEMBLY WITH HUB, SPLINED, 2DOF ARM, STAGE 2 ASSEMBLY	TALON 3B EOD	$5,545.00	0	$0.00
FB48190000399	MOTOR ASSEMBLY WITH HUB, SPLINED, 2 DOF ARM, STAGE 1	TALON 3B EOD	$5,545.00	0	$0.00
FB48190000399	MPL - KEY, 1/8" SQUARE, .355" LONG	TALON 3B EOD	$11.00	1	$11.00
FB48190000399 Total		**TALON 3B EOD**	**$11,101.00**		**$11.00**
FB48190000401	MPL - L PANEL ASSEMBLY, (POPULATED AND WIRED) (WITH SWITCHES AND HARNESSES)	TALON 3B EOD	$3,509.00	0	$0.00
FB48190000401	MOTOR ASSEMBLY WITH HUB, SPLINED, 2DOF ARM, STAGE 2 ASSEMBLY	TALON 3B EOD	$5,545.00	0	$0.00
FB48190000401	MPL - BRACE, MOTOR ASSEMBLY	TALON 3B EOD	$329.00	1	$329.00
FB48190000401	MOTOR ASSEMBLY WITH HUB, SPLINED, 2 DOF ARM, STAGE 1	TALON 3B EOD	$5,545.00	0	$0.00
FB48190000401 Total		**TALON 3B EOD**	**$14,928.00**		**$329.00**
FB48190000402	MPL-F, BATTERY, LITHIUM,RECHARGEABLE,11.1V,7200 MAH-AMREL LAPTOPS	PACKBOT FASTAC	$385.00	0	$0.00
FB48190000402 Total		**PACKBOT FASTAC**	**$385.00**		**$0.00**

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WONumber	Description	Project	Total Cost	AM Capable	AM Part Cost
FB48190000403	XBOX 360 WIRED USB CONTROLLER	MINI-EOD	$46.99	0	$0.00
FB48190000403 Total		**MINI-EOD**	**$46.99**		**$0.00**
FB48190000404	MPL - C-STACK, W/COFDM, GEN IV	MTRS TALON MK2	$20,129.00	0	$0.00
FB48190000404 Total		**MTRS TALON MK2**	**$20,129.00**		**$0.00**
FB48190000405	MOTOR ASSEMBLY WITH HUB, SPLINED, 2DOF ARM, STAGE	TALON ENGINEER	$5,545.00	0	$0.00
FB48190000405	MPL - ANTENNA, VEHICLE, DATA, 2.4 GHZ, 21" CABLE - WITH SPRING BASE ///REPLACES PN DSI-160-0893-1///	TALON ENGINEER	$1,172.00	0	$0.00
FB48190000405	MOTOR ASSEMBLY WITH HUB, SPLINED, 2 DOF ARM, STAG	TALON ENGINEER	$5,545.00	0	$0.00
FB48190000405	MPL - HARNESS ASSEMBLY, LOWER (BASE) ARM (MUST BE ORDERED BY REV. LEVEL)	TALON ENGINEER	$1,372.00	0	$0.00
FB48190000405 Total		**TALON ENGINEER**	**$13,634.00**		**$0.00**
FB48190000406	MPL-MF, GRIPPER FINGER BUMBER,(USED WITH MINI-EOD,	MINI-EOD	$0.47	1	$0.47
FB48190000406 Total		**MINI-EOD**	**$0.47**		**$0.47**
FB48190000414	MPL - L PANEL ASSEMBLY, (POPULATED AND WIRED) (WITH SWITCHES AND HARNESSES)	TALON ENGINEER	$3,509.00	0	$0.00
FB48190000414	MPL - TRACK ASSEMBLY, STANDARD (TWO TRACKS PER B	TALON ENGINEER	$1,067.00	1	$1,067.00
FB48190000414	MPL - HARNESS ASSEMBLY, SECOND ARM (MUST BE ORDERED BY REV. LEVEL)	TALON ENGINEER	$1,009.00	0	$0.00
FB48190000414	MPL - HARNESS ASSEMBLY, LOWER (BASE) ARM (MUST BE	TALON ENGINEER	$1,372.00	0	$0.00
FB48190000414	MPL - COVER, BALLISTIC NYLON GEN IIIB & GEN IV	TALON ENGINEER	$283.00	0	$0.00
FB48190000414 Total		**TALON ENGINEER**	**$7,240.00**		**$1,067.00**
FB48190000417	MPL - HARNESS ASSEMBLY, UPPER ARM	MTRS TALON MK2	$809.00	0	$0.00
FB48190000417	MPL - HARNESS MICROPHONE - GEN IV	MTRS TALON MK2	$397.00	0	$0.00
FB48190000417	MPL - BATTERY ADAPTER TRAY, VEHICLE, (HOLDS SIX PACK OF LITHIUM BB2590 BATTERIES)	MTRS TALON MK2	$2,485.00	1	$2,485.00
FB48190000417 Total		**MTRS TALON MK2**	**$3,691.00**		**$2,485.00**
FB48190000422	XBOX 360 WIRED USB CONTROLLER	MINI-EOD	$46.99	0	$0.00
FB48190000422	MPL-MF, MANIP,TURRET,CAM RNG FINDER(MINI-EOD)	MINI-EOD	$24,962.18	0	$0.00
FB48190000422 Total		**MINI-EOD**	**$25,009.17**		**$0.00**
FB48190000424	MPL-F, KIT,SMALL ARM MANIPULATOR,PACKBOT FASTAC (	PACKBOT FASTAC	$19,792.00	0	$0.00
FB48190000424 Total		**PACKBOT FASTAC**	**$19,792.00**		**$0.00**

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WONumber	Description	Project	Total Cost	AM Capable	AM Part Cost
FB48190000425	MPL -CABLE, ASSEMBLY, COAX, TNC JACK TO SMA R/A PLUG	TALON 3B EOD	$74.00	0	$0.00
FB48190000425 Total		**TALON 3B EOD**	**$74.00**		**$0.00**
FB48190000427	MPL - PCB, COMMS DISTRBUTION	TALON 3B EOD	$333.00	0	$0.00
FB48190000427	MPL - CABLE ASSEMBLY, RIBBON, 40 PIN	TALON 3B EOD	$75.00	0	$0.00
FB48190000427 Total		**TALON 3B EOD**	**$408.00**		**$0.00**
FB48190000431	MPL-F, CHASSIS ADAPTER,SCREW-ON COVER,PACKBOT	PACKBOT FASTAC	$673.20	1	$673.20
FB48190000431	MPL-F, ASSY,FLIPPER,PACKBOT FASTAC (TRACKLESS)	PACKBOT FASTAC	$1,002.00	1	$1,002.00
FB48190000431	MPL-F, KIT,SMALL ARM MANIPULATOR,PACKBOT FASTAC (SAM)	PACKBOT FASTAC	$19,792.00	1	$19,792.00
FB48190000431	MPL-F, KIT,CAMERA,SINGLE WIDE PAN TILT,PACKBOT FAST	PACKBOT FASTAC	$23,966.00	0	$0.00
FB48190000431	MPL-F, FABMACHINE, ARM PAYLOAD MOUNTING RAIL, PACKBOT EOD, ARM	PACKBOT FASTAC	$101.92	1	$101.92
FB48190000431 Total		**PACKBOT FASTAC**	**$45,535.12**		**$21,569.12**
FB48190000435	MPL-F, ASSY,FLIPPER,PACKBOT FASTAC (TRACKLESS)	PACKBOT FASTAC	$1,002.00	1	$1,002.00
FB48190000435	MPL-F, KIT,SMALL ARM MANIPULATOR,PACKBOT FASTAC (SAM)	PACKBOT FASTAC	$19,792.00	1	$19,792.00
FB48190000435	MPL-F, KIT,CAMERA,SINGLE WIDE PAN TILT,PACKBOT FAST	PACKBOT FASTAC	$23,966.00	0	$0.00
FB48190000435	MPL-F, ELEC STACK,BRAKES,PROGRAMMED,510FASTAC-24(2.4GHZ WITH AWARE 2)	PACKBOT FASTAC	$16,698.00	0	$0.00
FB48190000435	MPL-F, FABMACHINE, ARM PAYLOAD MOUNTING RAIL, PACKBOT EOD, ARM	PACKBOT FASTAC	$101.92	1	$101.92
FB48190000435	SCREW,MACH,440,1/4"L,PAN HEAD,PH,SS,SELF SEALING(HOUSING TO STACK)	PACKBOT FASTAC	$1.50	1	$1.50
FB48190000435 Total		**PACKBOT FASTAC**	**$61,561.42**		**$20,897.42**
FB48190000437	MPL-F, ASSY,FLIPPER,PACKBOT FASTAC (TRACKLESS)	PACKBOT FASTAC	$1,002.00	1	$1,002.00
FB48190000437	MPL-F, KIT,SMALL ARM MANIPULATOR,PACKBOT FASTAC (	PACKBOT FASTAC	$19,792.00	1	$19,792.00
FB48190000437	MPL-F, KIT,CAMERA,SINGLE WIDE PAN TILT,PACKBOT FASTAC (CAM)	PACKBOT FASTAC	$23,966.00	0	$0.00
FB48190000437 Total		**PACKBOT FASTAC**	**$44,760.00**		**$20,794.00**

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WONumber	Description	Project	Total Cost	AM Capable	AM Part Cost
FB48190000438	MPL - IDLER HUB BUSHING, FLANGED BEARING (SINGLE PC)	TALON ENGINEER	$32.00	0	$0.00
FB48190000438	MPL - MONITOR, OCU, DAYLIGHT READABLE, SINGLE CABL	TALON ENGINEER	$4,799.00	0	$0.00
FB48190000438 Total		**TALON ENGINEER**	**$4,831.00**		**$0.00**
FB48190000442	AMREL AC ADAPTER	PACKBOT FASTAC	$141.20	0	$0.00
FB48190000442 Total		**PACKBOT FASTAC**	**$141.20**		**$0.00**
FB48190000443	XBOX 360 WIRED USB CONTROLLER	MINI-EOD	$46.99	0	$0.00
FB48190000443 Total		**MINI-EOD**	**$46.99**		**$0.00**
FB48190000444	MPL - HARNESS MICROPHONE GEN IIIB	TALON ENGINEER	$488.00	0	$0.00
FB48190000444	ENCODER, ARM MOTOR	TALON ENGINEER	$115.00	0	$0.00
FB48190000444	MPL - IDLER HUB BUSHING, FLANGED BEARING (SINGLE PC	TALON ENGINEER	$16.00	1	$16.00
FB48190000444	MPL - L PANEL ASSEMBLY, (POPULATED AND WIRED) (WITH SWITCHES AND HARNESSES)	TALON ENGINEER	$3,509.00	0	$0.00
FB48190000444	MPL - ARM CHAIN ASSEMBLY	TALON ENGINEER	$747.00	1	$747.00
FB48190000444 Total		**TALON ENGINEER**	**$4,875.00**		**$763.00**
FB48190000445	MOTOR ASSEMBLY WITH HUB, SPLINED, 2DOF ARM, STAGE 2 ASSEMBLY	TALON 3B EOD	$5,545.00	0	$0.00
FB48190000445	MPL - TRACK ASSEMBLY, STANDARD (TWO TRACKS PER BOX)	TALON 3B EOD	$1,067.00	1	$1,067.00
FB48190000445	MOTOR ASSEMBLY WITH HUB, SPLINED, 2 DOF ARM, STAG	TALON 3B EOD	$5,545.00	0	$0.00
FB48190000445	MPL - HARNESS ASSEMBLY, SECOND ARM (MUST BE ORDERED BY REV. LEVEL)	TALON 3B EOD	$1,009.00	0	$0.00
FB48190000445 Total		**TALON 3B EOD**	**$13,166.00**		**$1,067.00**
FB48190000448	OGB-MF, TAC-EYE LT - IROBOT SYSTEM	MINI-EOD	$2,250.00	0	$0.00
FB48190000448	MPL-MF, BATTERY LATCH BAR	MINI-EOD	$24.00	1	$24.00
FB48190000448	MPL-MF, BATTERY LATCH MECHANICAL ASSY	MINI-EOD	$668.74	1	$668.74
FB48190000448	MPL-MF, CAMERA MOUNT PIVOT (USED WITH 91770A147)	MINI-EOD	$18.72	1	$18.72
FB48190000448	OGB-MF, 18-8 STAINLESS STEEL TRUSS HEAD PHILLIPS MACHINE SCREW,6-32 THREAD 7/16" LENGTH(USED WITH 4213563 & FRONT 4-BAR)	MINI-EOD	$0.05	1	$0.05
FB48190000448 Total		**MINI-EOD**	**$2,961.51**		**$711.51**

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WONumber	Description	Project	Total Cost	AM Capable	AM Part Cost
FB48190000449	MPL-F, ASSY,ANTENNA,4.9 GHZ,RCV (USED ON BOTH THE FASTAC AND THE MINI-EOD)	MINI-EOD	$365.65	0	$0.00
FB48190000449	MPL-MF, CAMERA MOUNT PIVOT (USED WITH 91770A147)	MINI-EOD	$18.72	1	$18.72
FB48190000449	OGB-MF, 18-8 STAINLESS STEEL TRUSS HEAD PHILLIPS MACHINE SCREW,6-32 THREAD 7/16" LENGTH(USED WITH 4213563 & FRONT 4-BAR)	MINI-EOD	$0.05	1	$0.05
FB48190000449 Total		**MINI-EOD**	**$384.42**		**$18.77**
FB48190000450	AMREL AC ADAPTER	PACKBOT FASTAC	$141.20	0	$0.00
FB48190000450 Total		**PACKBOT FASTAC**	**$141.20**		**$0.00**
FB48190000459	BLACK TRACK ASSY(1 SINGLE TRACK)	PACKBOT FASTAC	$310.00	1	$310.00
FB48190000459	MPL-F, ASSY,FLIPPER,PACKBOT FASTAC (TRACKLESS)	PACKBOT FASTAC	$1,002.00	1	$1,002.00
FB48190000459	MPL-F, KIT,SMALL ARM MANIPULATOR,PACKBOT FASTAC (SAM)	PACKBOT FASTAC	$19,792.00	1	$19,792.00
FB48190000459	MPL-F, KIT,CAMERA,SINGLE WIDE PAN TILT,PACKBOT FASTAC (CAM)	PACKBOT FASTAC	$23,966.00	0	$0.00
FB48190000459 Total		**PACKBOT FASTAC**	**$45,070.00**		**$21,104.00**
FB48190000460	SCREW,MACH,1032 X 2",PAN HD,PH,188 SS	PACKBOT FASTAC	$2.60	1	$2.60
FB48190000460	BLACK TRACK ASSY(1 SINGLE TRACK)	PACKBOT FASTAC	$310.00	1	$310.00
FB48190000460	MPL-F, ASSY,PLATE,LEFT SIDE,PACKBOT FASTAC	PACKBOT FASTAC	$4,959.00	1	$4,959.00
FB48190000460	MPL-F, ASSY,REAR TUBE,NO GPS,PACKBOT FASTAC	PACKBOT FASTAC	$6,340.00	1	$6,340.00
FB48190000460	MPL-F, ELEC STACK,BRAKES,PROGRAMMED,510FASTAC-24(2.4GHZ WITH AWARE 2)	PACKBOT FASTAC	$16,698.00	0	$0.00
FB48190000460	SCREW,MACH,440,1/4"L,PAN HEAD,PH,SS,SELF SEALING(HOUSING TO STACK)	PACKBOT FASTAC	$1.50	1	$1.50
FB48190000460 Total		**PACKBOT FASTAC**	**$28,311.10**		**$11,613.10**
FB48190000461	MPL - HARNESS ASSEMBLY, SECOND ARM (MUST BE ORDERED BY REV. LEVEL)	TALON ENGINEER	$1,009.00	0	$0.00
FB48190000461	MPL - HARNESS ASSEMBLY, LOWER (BASE) ARM (MUST BE ORDERED BY REV. LEVEL)	TALON ENGINEER	$1,372.00	0	$0.00
FB48190000461	MPL - CAMERA, REMOTE CONTROLLED ZOOM (40:1)	TALON ENGINEER	$2,434.00	0	$0.00
FB48190000461 Total		**TALON ENGINEER**	**$4,815.00**		**$0.00**

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WONumber	Description	Project	Total Cost	AM Capable	AM Part Cost
FB48190000462	FUSE (F1343CT-ND) POWER DISTRIBUTION BOARD, 1 AMP	TALON ENGINEER	12	0	0
FB48190000462	MPL - IDLER HUB BUSHING, FLANGED BEARING (SINGLE PC)	TALON ENGINEER	8	1	8
FB48190000462	MOTOR ASSEMBLY WITH HUB, SPLINED, 2DOF ARM, STAGE 2 ASSEMBLY	TALON ENGINEER	5545	0	0
FB48190000462	MOTOR ASSEMBLY WITH HUB, SPLINED, 2 DOF ARM, STAGE 1	TALON ENGINEER	5545	0	0
FB48190000462	MPL - QUICK RELEASE (ARM RETENTION) PIN, MODIFIED	TALON ENGINEER	438	1	438
FB48190000462 Total		**TALON ENGINEER**	**11548**		**446**
FB48190000463	MPL-F, CABLE ASSY, RADIO -1900 TO 4750MHZ, SMA TO RI	PACKBOT FASTAC	$207.00	0	$0.00
FB48190000463 Total		**PACKBOT FASTAC**	**207**		**0**
FB48190000466	MPL - CABLE ASSEMBLY, POWER SWITCH, GEN IV	MTRS TALON MK2	311	0	0
FB48190000466 Total		**MTRS TALON MK2**	**311**		**0**
FB48190000467	MPL-F, CHASSIS ADAPTER,SCREW-ON COVER,PACKBOT	PACKBOT FASTAC	673.2	1	673.2
FB48190000467	MPL-F, ASSY, MAIN ELEC HOUSING, PACKBOT FASTAC (STACK HOUSING)	PACKBOT FASTAC	2910	1	2910
FB48190000467	MPL-F, ASSY,BOGIE,PACKBOT FASTAC	PACKBOT FASTAC	1455	1	1455
FB48190000467	MPL-F, ASSY,HANDLE STRAP,CHASSIS,PACKBOT FASTAC	PACKBOT FASTAC	166.25	1	166.25
FB48190000467	MPL-F, 2.4 GHZ DIRECTIONAL ANTENNA ASSEMBLY	PACKBOT FASTAC	180	0	0
FB48190000467	MPL-F, ELEC STACK,BRAKES,PROGRAMMED,510FASTAC-24(2.4GHZ WITH AWARE 2)	PACKBOT FASTAC	16698	0	0
FB48190000467	SCREW,MACH,440,1/4"L,PAN HEAD,PH,SS,SELF SEALING(HOUSING TO STACK)	PACKBOT FASTAC	7.5	1	7.5
FB48190000467 Total		**PACKBOT FASTAC**	**22089.95**		**5211.95**

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WONumber	Description	Project	Total Cost	AM Capable	AM Part Cost
FB48190000475	MPL-F, ASSY,ANTENNA,4.9 GHZ,RCV (USED ON BOTH THE FASTAC AND THE MINI-EOD)	MINI-EOD	365.65	0	0
FB48190000475	OGB-MF, TAC-EYE LT - IROBOT SYSTEM	MINI-EOD	2250	0	0
FB48190000475	MPL-MF, ASSY,TRACK,FLIPPER,MINI-EOD	MINI-EOD	96.46	1	96.46
FB48190000475	MPL-MF, ASSY,TRACK,MAIN,MINI-EOD	MINI-EOD	222.04	1	222.04
FB48190000475	MPL-MF, BATTERY LATCH BAR	MINI-EOD	24	1	24
FB48190000475	MPL-MF, BATTERY LATCH MECHANICAL ASSY	MINI-EOD	668.74	1	668.74
FB48190000475	MPL-MF, CAMERA MOUNT PIVOT (USED WITH 91770A147)	MINI-EOD	18.72	1	18.72
FB48190000475	OGB-MF, 18-8 STAINLESS STEEL TRUSS HEAD PHILLIPS MACHINE SCREW,6-32 THREAD 7/16" LENGTH(USED WITH 4213563 & FRONT 4-BAR)	MINI-EOD	0.05	1	0.05
FB48190000475 Total		**MINI-EOD**	**3645.66**		**1030.01**
NOCODE0000338	MPL - PC BOARD, POWER DISTRIBUTION E-BOX ///REPLACES RDSI-01047///	TALON 3B EOD	$581.00	0	$0.00
NOCODE0000338	MPL ARMSUBASSEMBLY TALONIIIB W/CABLES W/O GRIPPE	TALON 3B EOD	$19,543.00	0	$0.00
NOCODE0000338	MPL - MANIFOLD, E-BOX	TALON 3B EOD	$3,460.00	0	$0.00
NOCODE0000338	MPL - E-BOX STACK	TALON 3B EOD	$7,973.00	0	$0.00
NOCODE0000338	MPL - HARNESS ASSEMBLY, AMC PHASE (RED, WHITE, BLUE)	TALON 3B EOD	$217.00	0	$0.00
NOCODE0000338	MPL - COVER, BALLISTIC NYLON GEN IIIB & GEN IV	TALON 3B EOD	$283.00	0	$0.00
NOCODE0000338 Total		**TALON 3B EOD**	**$32,057.00**		**$0.00**
NOCODE0000349	MPL - MOTOR ARM ASSEMBLY	TALON ENGINEER	$5,176.00	0	$0.00
NOCODE0000349	MPL - KEY, 1/8" SQUARE, .355" LONG	TALON ENGINEER	$11.00	1	$11.00
NOCODE0000349	MPL - HUB, ARM MOTOR, STAINLESS STEEL, LOWER	TALON ENGINEER	$281.00	1	$281.00
NOCODE0000349 Total		**TALON ENGINEER**	**$5,468.00**		**$292.00**
NOCODE0000350	MPL - BATTERY ADAPTER TRAY, VEHICLE, (HOLDS SIX PAC	TALON 3B EOD	$2,485.00	1	$2,485.00
NOCODE0000350 Total		**TALON 3B EOD**	**$2,485.00**		**$2,485.00**
NOCODE0000351	BLACK TRACK ASSY(1 SINGLE TRACK)	PACKBOT FASTAC	$310.00	1	$310.00
NOCODE0000351 Total		**PACKBOT FASTAC**	**$310.00**		**$310.00**
NOCODE0000352	MPL-MF, ASSY,TRACK,MAIN,MINI-EOD	MINI-EOD	$222.04	1	$222.04
NOCODE0000352	MPL-MF, ASSY,FLIPPER,MINI-EOD(OLD PART# 4146847)	MINI-EOD	$1,925.86	1	$1,925.86
NOCODE0000352 Total		**MINI-EOD**	**$2,147.90**		**$2,147.90**

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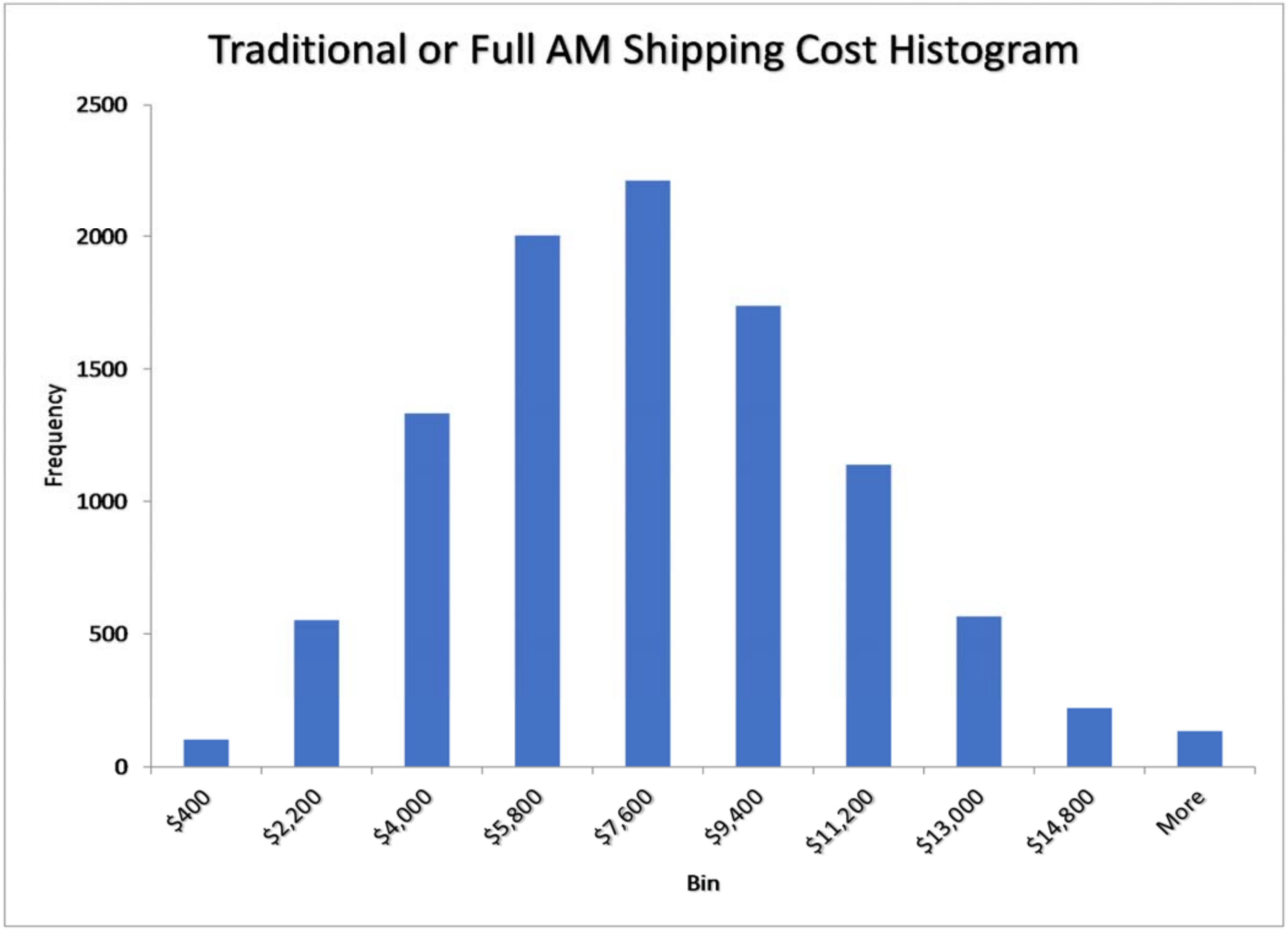
APPENDIX B: Annual Cost Histograms

Bin	*Frequency*
$400	101
$2,200	553
$4,000	1335
$5,800	2006
$7,600	2212
$9,400	1742
$11,200	1137
$13,000	564
$14,800	218
More	132



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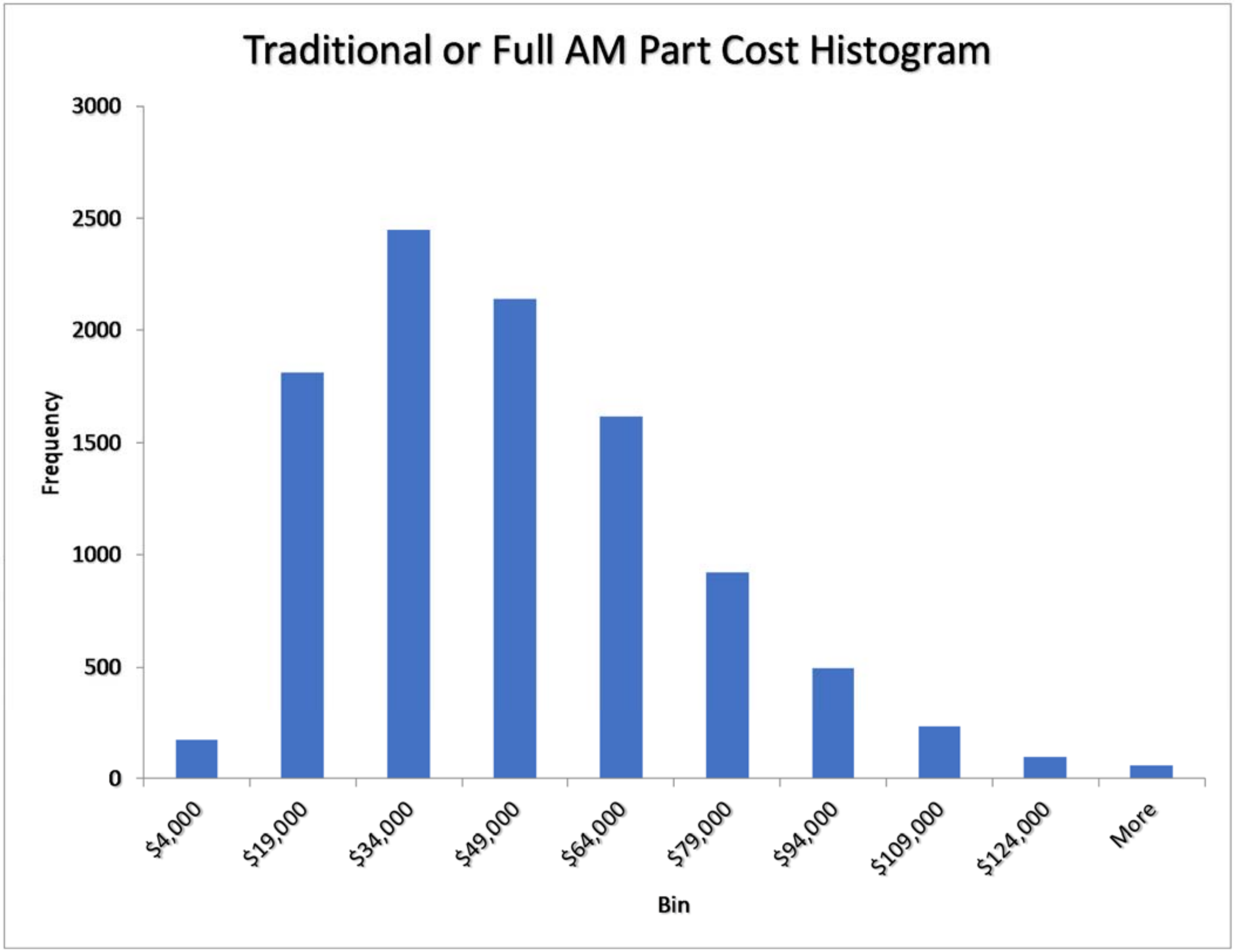

Bin	*Frequency*
$4,000	174
$19,000	1815
$34,000	2449
$49,000	2140
$64,000	1618
$79,000	921
$94,000	493
$109,000	232
$124,000	97
More	61

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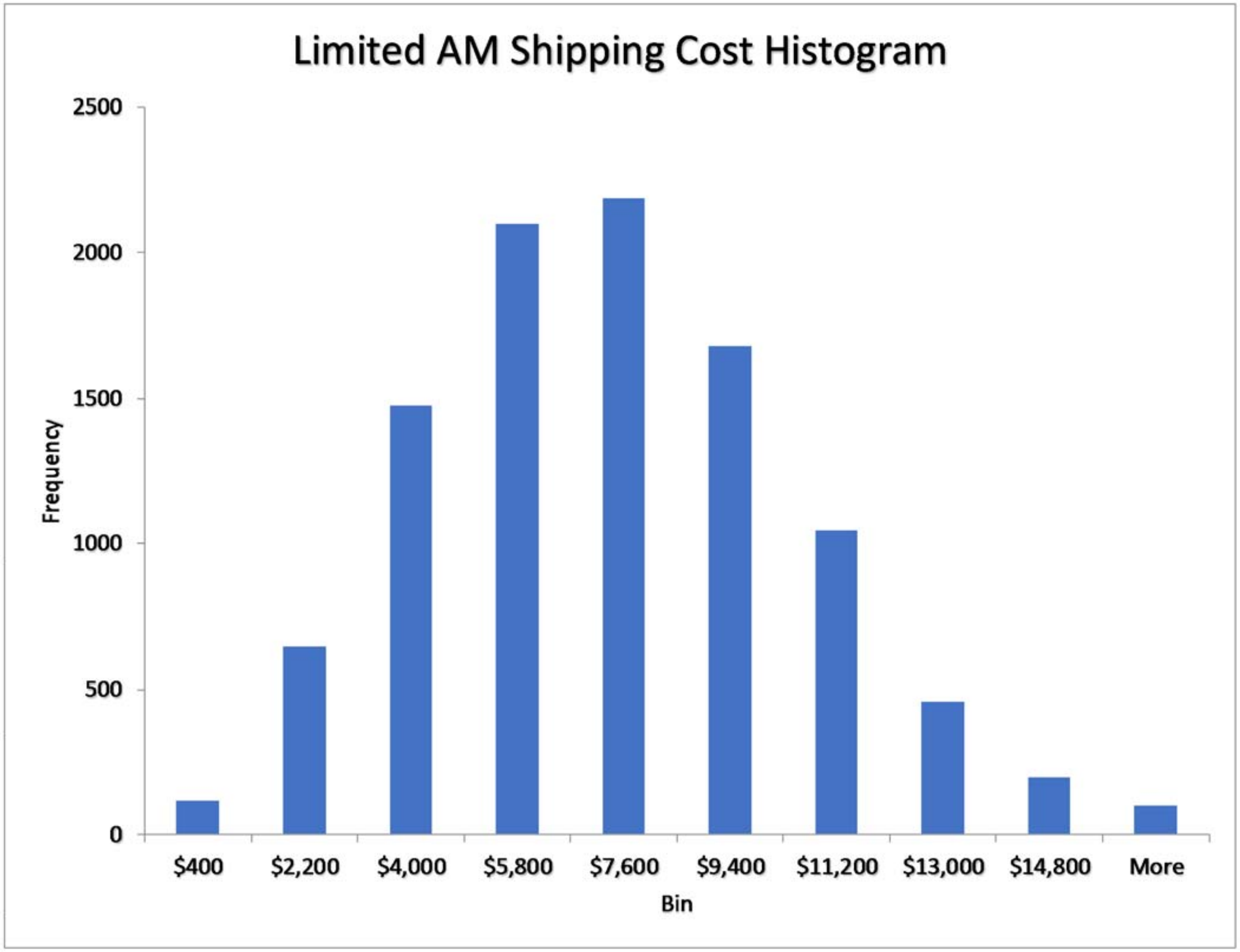

Bin	*Frequency*
$400	118
$2,200	646
$4,000	1474
$5,800	2101
$7,600	2188
$9,400	1676
$11,200	1045
$13,000	456
$14,800	195
More	101

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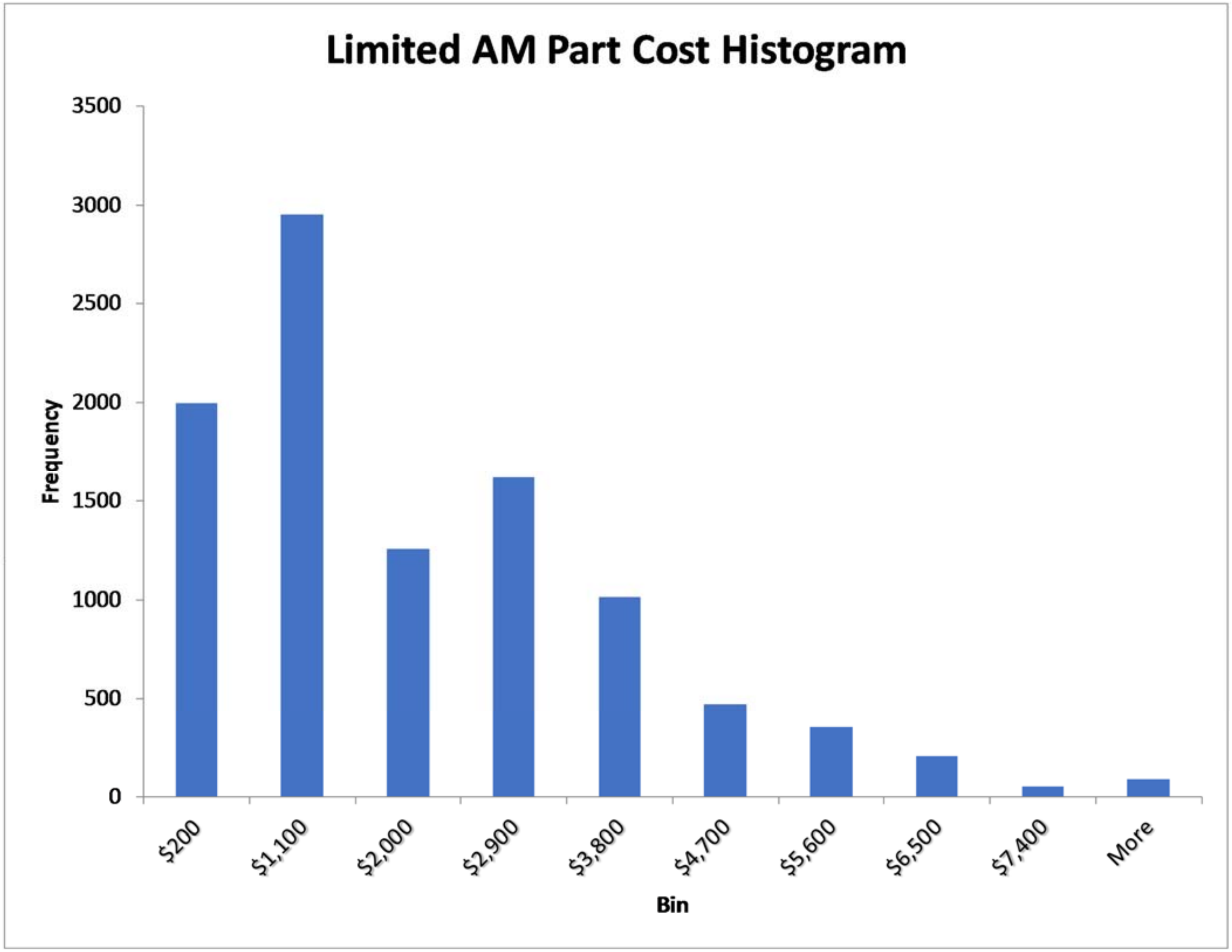
Bin	*Frequency*
$200	1994
$1,100	2949
$2,000	1254
$2,900	1617
$3,800	1012
$4,700	472
$5,600	353
$6,500	208
$7,400	51
More	90



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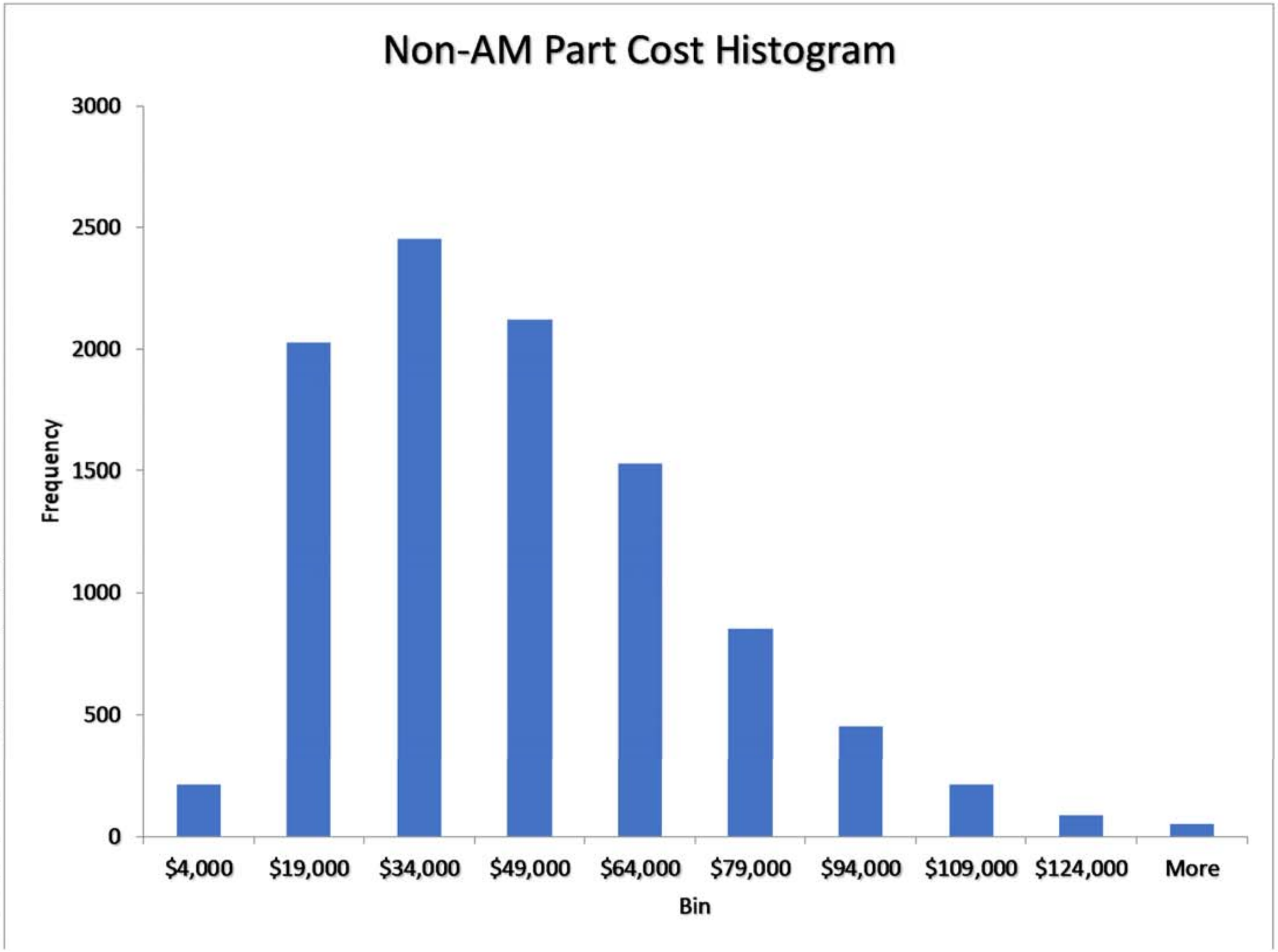
Bin	*Frequency*
$4,000	213
$19,000	2028
$34,000	2452
$49,000	2124
$64,000	1529
$79,000	849
$94,000	451
$109,000	214
$124,000	86
More	54



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14. ABSTRACT

Additive manufacturing is mandated as a technology for the Department of Defense to consider to implement. Previous efforts have shown positive potential for additive manufacturing (AM) for United States Air Force Civil Engineering but do not explore the economic impact. This research examines implementation by investigating a specific Explosive Ordnance Disposal repair part supply chain in the current combat theater of operations. A framework to capture the basic financial savings AM could realize was developed to aid AM decision making. This research established a Scenario Planning and Monte Carlo simulation based framework to produce an estimated annual cost for a system with various configurations and machine capabilities under varied machine life lengths. The model informs the baseline value of AM replacement and what this represents for an associated machine cost. Further, the research presents potential roadblocks and additional cost areas that would impact an AM decision. The overall results take the next step to understand AM's implementation for the United States Air Force and Civil Engineer Squadrons.

15. SUBJECT TERMS
Additive Manufacturing, Supply Chain, Air Force, Civil Engineer Squadron

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