A DELPHI STUDY OF ADDITIVE MANUFACTURING APPLICABILITY FOR UNITED STATES AIR FORCE CIVIL ENGINEER CONTINGENCY OPERATIONS

THESIS

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Abstract

Additive manufacturing is a relatively new technique that is gaining popularity in many applications. This research examines the possibilities for the integration of additive manufacturing (AM) machines in United States Air Force civil engineer (CE) contingency operations. A Delphi study was conducted that combined the knowledge and experience of experts in both the AM industry and the Air Force CE community to forecast the possible benefits and drawbacks of this novel AM application.

The results of this Delphi study indicate that including an AM machine would be beneficial in meeting deployed Air Force CE requirements. Further, AM technology has reached a point that a pilot study would be beneficial to validate the benefits of including an AM machine in CE operations. Proposed goals of, and a design for this study are presented. Further, the results indicate that within the next five years, AM technology will have progressed far enough that a full-scale deployment of AM machines to meet Air Force CE contingency requirements will be beneficial.

To my family, all FIVE of you:

To my amazing wife who did more than her share at home while I completed this research, especially all those times I didn't have class but was still at school…

To my kids who never understood why daddy always stayed at school so long.

Despite the late nights and missed weekends,
thanks for always greeting me at the door with a smile!

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Seth N. Poulsen

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A DELPHI STUDY OF ADDITIVE MANUFACTURING APPLICABILITY FOR UNITED STATES AIR FORCE CIVIL ENGINEER CONTINGENCY OPERATIONS

I. Introduction

Additive manufacturing is a relatively new technique that is gaining popularity in many applications. One of these developing applications is the use of additive manufacturing machines for the production of supplies in remote, austere, or deployed locations. United States Air Force civil engineers are one of the many organizations that often labor in such contingency environments, yet no research to date has addressed the application of additive manufacturing for Air Force civil engineers in these locations. This research endeavors to determine how additive manufacturing techniques can be beneficially applied in Air Force civil engineer contingency operations and to predict the appropriate timeframe for this novel application.

General Issue

United States Air Force (USAF) civil engineers (CEs) are responsible for the construction, operation, maintenance, repair, and disposal of USAF civil infrastructure on Air Force bases throughout the United States and abroad. These CEs manage a diverse portfolio of infrastructure that includes facilities, roads, runways, water distribution, and other systems. CEs are responsible for these systems not only on large, primary bases, but also in contingency locations that are often remote, isolated, and austere.

Maintaining infrastructure at contingency locations poses unique and significant challenges. One of these challenges, and the focus of this research, is the supply of tools and parts required for infrastructure maintenance activities. Due to their remote and isolated nature, contingency locations often prove to be challenging to supply. As a result, initial CE teams typically deploy to these sites with a toolkit that provides them with an initial capability to maintain and repair infrastructure.

These deployable CE toolkits are known as Unit Type Code toolkits, or equipment-only UTCs. There are dozens of different CE UTCs, each of which provides a unique capability. UTCs can consist of supplies and tools, personnel, or both. The CE kits examined in this thesis will be equipment-only UTCs that contain the tools, spare parts, and materials necessary for construction and maintenance of infrastructure systems. These UTC toolkits are designed for use in a generalized situation and are not tailored to the specific environment or location into which they will be deployed. Additionally, they are designed to be air lifted by small cargo aircraft into a remote location and are therefore limited in size and contents. The ability to create location-specific tools and parts on site, as needed, could be beneficial in reducing the size and general nature of equipment-only CE UTCs.

One promising option for establishing a more site-specific, compact capability is the inclusion of additive manufacturing (AM) machines in certain CE UTCs. Additive manufacturing is the process of constructing objects in three dimensions by bonding a material in successive, thin layers. The end result is a product that is built “from the ground up” rather than milled down from a block of material or cast in a mold, as is common in conventional manufacturing processes. AM allows more precision and flexibility in the design and structure of manufactured parts. It also allows for the creation of thousands of possible parts or tools from a single machine. These benefits of precision and flexibility in design and manufacturing show promising possibilities for addressing the general nature of CE UTC toolkits, decreasing their overall size, and increasing their capabilities.

Problem Statement

Although AM is a promising technology for use in equipment only UTCs, no research has been conducted to date on this topic. This research will determine the qualities of an AM machine that would make it suitable for such applications and the types of AM machines that are currently well suited for these UTCs. Air Force CEs presently do not know if current AM technology has reached a point that it is suitable for this application. The Air Force Civil Engineer Center (AFCEC) is interested in the possible AM applications for CEs and has deemed this topic warrants further investigation. Therefore, AFCEC sponsored this research in an effort to further understand the possible applications of AM in CE UTCs.

Research Objective and Investigative Questions

The overall objective of this research is to determine if (1) additive manufacturing machines would be beneficial if included in CE equipment UTCs and (2) to predict the appropriate timeframe for this inclusion. To further define this objective, three more-specific investigative questions were created to guide this research. These questions are:

1) *What categories of AM machine are currently well suited for utilization in CE equipment UTCs?*

   Many types, makes, and models of AM machines are on the market today. This question seeks to understand which of these various machines would be suitable for CE applications. This question does not look at companies or brands, but instead analyzes the various raw materials and build processes currently available in the AM industry.

2) *What attributes make an AM machine well suited for use in a CE equipment UTC?*

   This question focuses on the specific attributes necessary in an AM machine for CE contingency applications. It seeks to understand the desired qualities of an ideal AM machine and will focus on machine "-ilities" such as reliability, usability, quality, maintainability, and others. These properties are not necessarily fundamental requirements of an AM machine, but knowing which of these attributes are most important can assist in selecting the best machine for contingency engineering (de Weck, Roos, & Magee, 2011:66).

3) *Has the AM industry currently reached a point at which the selected categories of AM machines embody these beneficial attributes?*

   This question seeks to understand the status of current AM practices and future possibilities. AM is not a new technology; in fact, similar methods for creating objects layer by layer have been in use since the 1890s (Bourell, Beaman Jr., Leu, & Rosen, 2009:5). Since that time, AM technology has been continually progressing. This question seeks to determine if AM technology has progressed far enough today, or if the technology needs to further mature, to be suitable for CE contingency applications.

Together, these questions further define the goal of this thesis effort. They shape the literature review, the methodology, and the analysis. These questions will be referenced later in this document when the methodology and results are discussed.

Research Approach

This thesis is the culmination of multiple stages of research. The research begins with a literature review that elucidates the current state of AM technologies. This review describes the current AM machine types, benefits, and limitations. Additionally, this review describes past and current applications of AM machines in contingency locations.

This document next presents the Delphi technique used in this research. The Delphi study elicited and consolidated the views of a panel of AM and CE UTC experts. The objective of this study is to better understand the current possibilities for AM technology in CE UTCs and to determine possible future applications of this technology. This study combined and refined the cumulative knowledge of these experts through multiple rounds of questions that address this topic.

After each round of questioning, the Delphi method used statistical analysis to highlight the level of agreement among the panel participants. The information gathered from the Delphi questionnaires and analysis was used to generate findings and recommendations. These findings illustrate the future possibilities for AM in Air Force CE contingency operations. The recommendations include possible applications for AM machines and suggestions for further research that would be beneficial for this subject.

Thesis Overview

This document follows the traditional five-chapter thesis format. Succeeding this introductory chapter, Chapter II reviews the current literature on AM technology. Chapter III discusses the method utilized in this research, the Delphi study technique. Chapter IV presents the opinions of the panel collected in the Delphi study and describes the analysis of this information. Finally, Chapter V discusses the findings and recommendations of this research and provides suggestions for follow-on research.

II. Literature Review

Chapter Overview

This chapter summarizes the literature review conducted for this research, which provides background information on several topics. First, Air Force CE UTC utilization and management is discussed. Second, an overview of the current situation of the AM industry is presented. Third, some of the geopolitical, economic, and environmental benefits of AM are presented. Next, several current applications for AM technology in military applications and contingency locations are examined and discussed. Finally, the chapter concludes with a discussion of the Delphi method, including its strengths and proper application.

Unit Type Codes

USAF CEs are responsible for the maintenance and construction of civil infrastructure on AF installations worldwide. This includes large, primary installations but also includes smaller, remote, isolated, and austere, contingency locations. When CEs deploy to these contingency locations, they typically do so with a toolkit to perform construction, maintenance, and repair activities. These toolkits are known as Unit Type Code toolkits, or UTCs.

Air Force UTCs.

The Air Force defines a UTC as “a potential capability focused upon accomplishment of a specific mission that the military service provides” (United States Department of the Air Force, 2006:87). Therefore, each UTC is not just a toolkit: it is an enabler used to accomplish a certain mission or task. A UTC may include tools, equipment, and supplies and it may also include AF personnel (United States Department of the Air Force, 2006:87). Some UTCs consist only of equipment, some contain only personnel, and some are a combination of both personnel and equipment.

Every UTC is identified by several pieces of information, a unique number, a Mission Capabilities Statement (MISCAP), a personnel number, and a material weight. The number that defines each UTC is a five-digit alphanumeric code, which uniquely identifies a UTC and indicates the functional area responsible for the UTC. The MISCAP is a brief "statement of the capabilities of the force identified by each UTC" (United States Department of the Air Force, 2012:66). The personnel number associated with each UTC is known as the Authorized Personnel (AUTH) number. This number indicates the quantity of personnel assigned to a specific UTC; it is zero if no personnel are assigned to a UTC. The weight for a UTC indicates the weight of all material contained in the kit in total short tons (ST). This value is crucial for determining the options for deploying a UTC. This number is zero if the UTC consists of personnel only (United States Department of the Air Force, 2012:66).

UTC Utilization.

When planning for military or contingency situations, war planners use UTCs to understand and anticipate the total manpower and logistics chain required to support an operation (United States Department of the Air Force, 2012:66). A war planner anticipating a military requirement will turn to a list of UTCs to find a predefined capability that will meet the need. Thus, a UTC is the basic building block utilized to meet peacekeeping, humanitarian relief, and rotational operation needs in contingencies from small to large scale (United States Department of the Air Force, 2006:88).

Equipment UTCs are warehoused and maintained at a primary base in the continental United States. When needed, an equipment-only UTC will be picked up from its storage location and delivered via air cargo to the requisite deployed location. This system allows for the UTC to be continually maintained and ready for rapid deployment at any time (United States Department of the Air Force, 2006:88).

Civil Engineer UTCs.

The USAF maintains thousands of UTCs and of these, 96 are specific to CEs (Grissett, 2014). CE-specific UTCs are designated as "4F9XX," where "XX" indicates the designation for a specific UTC. These UTCs meet a variety of engineering needs and each is specifically tailored to provide a capability that may be needed in a wide range of contingency environments. Two general engineering kits will be examined in further detail: the 4F9ET Engineer Force Equipment Kit and the 4F9RY RED HORSE Equipment Kit. The MISCAPS for these UTCs are given in Table 1.

Table 1. 4F9ET & 4F9RY Mission Capability Statements

UTC	MISCAP
4F9ET	Engineer force equipment set to support two 4FPET UTCs. Supports missions (including recovery) to establish, operate, and sustain contingency operating locations, aerial ports, enroute bases, natural disaster recovery operations and joint-base support. Provides equipment for initial beddown of bare base and/or forward operating locations. May be augmented with one or more 4F9EF UTCs based on mission requirements.
4F9RY	Red Horse (RH) equipment UTC to support lead C2 element (hub) of a deployed RH squadron responsible for managing RH construction projects in a theatre of operations. Must be combined with a 4FPRY UTC to support RH beddown. Vehicle maintenance, services, design, and engineering support surveying, drafting, and material testing capabilities. Requires a 4F9GP UTC for precision survey requirements using global positioning system equipment. Horizontal/vertical construction capability is obtained when combined with one or more of the following RH UTC combinations. Horizontal construction teams 4F9RU/4FPRU or 4F9RV/4FPRV UTCs and/or vertical construction teams 4F9RS/4FPRS or 4F9RT/4FPRT UTCs. When combined with a 4FPRY, this UTC contains enhanced logistics and communication capability.

The 4F9ET is a general engineer force equipment kit used for light construction. It is an equipment-only UTC and is designed to be paired with two personnel-only UTCs. When these three UTCs are deployed together, the capability to establish, operate, and sustain a contingency location is delivered. This kit contains basic tools and equipment for electricians, structural craftsmen, pavements craftsmen, heating ventilation and cooling (HVAC) technicians, and others. Some of the items included are hammers, saws, tape measures, pliers, rakes, crowbars, concrete floats, drills, chisels, screwdrivers, levels, helmets, padlocks, ladders, and other tools needed to establish and maintain an air base (Air Force Civil Engineer Center, 2014).

The 4F9RY is a basic UTC for heavy construction. This kit, tailored for use by a Rapid Engineer Deployable Heavy Operational Repair Squadron Engineer (RED HORSE) unit, has more-robust capability for construction, paving, and logistics. This kit is an equipment-only kit designed to be used by the RED HORSE personnel in the

4FPRY UTC. The kit includes many items that are in the 4F9ET and adds larger items like power distribution panels, latrines, heaters, water purification systems, a tactical radio kit, a welding kit, fuel tanks and pumps, a skid steer loader, trucks and tents (Air Force Civil Engineer Center, 2014).

Additive Manufacturing

The process of additive manufacturing is a relatively new method for creating three-dimensional (3D) objects from a supply of raw material. AM is the process of constructing objects in three dimensions by bonding a material in successive, thin layers. The end result is a product that is built “from the ground up” rather than milled down from a block of material or cast in a mold, as is common in conventional manufacturing processes. There are three main steps in AM: digital design, production, and post-processing.

The first step to AM production of any object is to digitally create the object in a computer 3D modeling software program. This can be accomplished by direct creation in the program or by laser scanning to create a digital model of a physical object. The final digital model is then transferred to the AM machine for production.

In the production phase, the AM machine receives the digital model and produces the object utilizing the desired material. This step is accomplished one thin layer at a time. Each layer is fused to the layer below it, incrementally building up a 3D part from the supply of raw material. When production is complete, the object can be removed for post-processing.

The final phase of AM is post-processing, which includes all the steps necessary to make the part produced by AM complete and useable. Items manufactured in most AM machines will require several steps of post-processing. Some of these steps may include cleaning, removing construction supports, or curing the item produced in the machine.

First, a part created in an AM machine will typically have leftover raw material on or around its exterior, which must be removed. For example, in poweder-based AM processes, the item produced must be removed from a block of excess raw material powder. In liquid-based AM processes, the coating of unhardened liquid raw material must be washed off the exterior of the item.

Second, several varieties of AM machines produce support columns or structures while producing objects that must be removed in post-procesing. The use of these supports ensures the structural integrity of the item during the production process. These structures allow AM machines to create more complex geometries, but serve no purpose for the final part. Some supports can be removed by dissolving them in a liquid and others must be mechanically separated by clipping, cutting, or milling.

Third, for some AM machines, the objects produced do not attain their full material properties during production. Parts produced by these machines require some form of setting or curing to achieve their final strength and hardness. This curing is typically accomplished by ultraviolet light or by heat.

Additive Manufacturing Processes.

Many types of AM machines are found in industry today. Although every machine is similar in that it creates a three-dimensional item by combining multiple layers of material, each type of machine approaches the task in a different way and uses different materials. This research has adopted the classification system established by the American Society for Testing and Materials (ASTM) to sort the various types of machine into groups. The ASTM has divided the various AM machines into seven categories based on the machine's production process: binder jetting, directed-energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization (ASTM International, 2012:1). Each category of AM machine will be further defined in this section and a brief synopsis of each is given in Table 2.

Table 2. Additive Manufacturing Categories (ASTM International, 2012)

METAL/POLYMER

Powder Bed Processes

1) Powder Bed Fusion

AM process in which thermal energy selectively fuses regions of successive layers of powdered raw material

- Laser Processes
  - Selective Laser Melting (SLM) **METAL**
  - Selective Laser Sintering (SLS) **POLYMER**
  - Selective Mask Sintering (SMS) **METAL**
- Electron Beam Melting (EBM) **METAL**

2) Binder Jetting

AM process in which a liquid bonding agent is selectively deposited to join powdered raw materials

- Powder Bed Binder Jetting (**POLYMER**)
- 3DPrinting (**METAL**)

3) Directed-Energy Deposition

AM process in which focused thermal energy fuses raw materials by melting as they are being deposited

- Powder Feed (**METAL**)
- Wire Feed (**METAL**)

POLYMER

4) Vat Photopolymerization

AM process in which a liquid raw material in a vat is selectively cured by light activated polymerization

- Stereolithography (SLA)
- Flash Curing
- Film Transfer Imaging (FTI)

5) Material Extrusion

AM process in which raw material is selectively dispensed through a nozzle or orifice

- Fused Deposition Modeling (FDM)

6) Material Jetting

AM process in which droplets of raw material are selectively deposited

- Drop-on-Demand (DoD)
- Multijet Modeling

OTHER (typically paper, sometimes metal or polymer)

7) Sheet Lamination

AM process in which sheets of raw material are bonded to form an object.

- Ultrasonic Consolidation (UC)
- Adhesive Bonding

Powder Bed Fusion.

Selective laser sintering (SLS) and selective laser melting (SLM) machines spread a layer of powdered material, either metal or polymer, and then use a laser to melt or sinter the material together. Two benefits of this process are that (1) support structures are not required during production and (2) multiple layers of items may be produced in one job. Because of these benefits, this process is a promising option for traditional mass production manufacturing. Unfortunately, this process is very sensitive to changes in temperature and humidity so the build chamber is generally heat and atmosphere controlled. A skin-and-core strategy is typically used: the outside of each part in the layer is first traced and then the inside of the part is solidified. The interior is often solidified more sparsely as less strength is typically needed inside a part (Kuhn & Collier, 2014).

The electron beam melting (EBM) process is much like SLS/SLM except it uses an electron beam rather than a laser to melt or sinter the raw material. This process does not require support structures during production, but must be conducted in a vacuum and at high temperatures. As a result, this method yields high-strength parts with low residual stress (Kuhn & Collier, 2014).

Powder Bed Binder Jetting.

Powder bed binder jetting also begins with a thin layer of powdered material. A binder material is used to bond the materials in the desired shape. This bonding material can remain in place for polymer processes. In metal processes, the bonding material is baked out and the resulting voids in the part are infiltrated with another material. This results in an inhomogeneous material, as the part is constructed of one material and infiltrated with another. Powder bed binder jetting requires no support structures and allows production of multiple layers of parts in one job.

Directed Energy Deposition.

In directed energy deposition, the powdered raw material is shot from a nozzle toward a beam of energy, with which it merges just above the build surface and the material melts and is added to the part. This process is unique in that it can be used to coat existing parts in addition to creating new parts. The raw material can also be continually varied throughout a job, resulting in graded materials (Kuhn & Collier, 2014).

Vat Photopolymerization Process.

In vat photopolymerization, a thin layer of liquid is activated by ultraviolet (UV) light. The liquid resin cures (polymerizes) locally in “bullet” shapes. This type of machine can produce very smooth and rounded shapes. In post processing, support structures must be removed and UV curing is required to cure the excess material between the “bullets” to develop full part strength. However, the parts produced using this process are susceptible to aging problems, such as increased brittleness, due to light and heat sensitivity. This process is often used to create molds for casting that are burned off after casting is complete. It is also common in manufacturing individually tailored hearing aids and braces (Kuhn & Collier, 2014).

Material Extrusion.

In material extrusion, lines of a solid raw material are extruded from a heated orifice. This process resembles creating a part by “drawing” it in 3D with a hot glue gun. This method requires support structures, which are typically created from a second material that must be removed in post-processing (Kuhn & Collier, 2014). The most common method of material extrusion is Fused Deposition Modeling (FDM). This simple process is the basis for most consumer-grade desktop AM machines, commonly known as 3D printers (Pham & Gault, 1998:1270).

Material Jetting.

In material jetting, a print head places a heated material down layer by layer. This process resembles producing a part by "printing" it with an inkjet printer. A separate support material is also produced the same way. Polyjet or multijet machines of this type are common. The materials used in this process are typically photosensitive and are cured during post processing with ultraviolet light to increase strength (Kuhn & Collier, 2014).

Sheet Lamination.

Sheet lamination is the process of combining solid layers of a raw material. In this process, sheets or strips of the material are utilized. This process can be accomplished by gluing layers of paper or plastic together, by melting layers of plastic together, or by joining layers of metal together by welding or with bolts (Kuhn & Collier, 2014). It is one of the oldest varieties of AM, dating back to the 1890s (Bourell, Beaman Jr., Leu, & Rosen, 2009:5).

Current State of the Additive Manufacturing Industry.

AM has been dubbed a "disruptive technology" (Campbell & Ivanova, 2013:67) and has been identified as a technology that may very well create a new "Industrial Revolution" (Prince, 2014:39). Additionally, the technology is being explored and expanded by armed forces organizations for military purposes. It is also beginning to be explored as an option for contingency and austere applications. Each of these applications is important to review in considering AM for CE contingency applications and will be further discussed in this section.

Additive Manufacturing as a Disruptive Technology.

A disruptive technology is one that completely changes the way an industry or process is operated. More specifically, disruptive technologies are considered "scientific discoveries that break through the usual product/technology capabilities and provide a basis for a new competitive paradigm" (Kostoff, Boylan, & Simone, 2004:142). AM falls into this disruptive category for three reasons. First, AM is a new process that changes the traditional manufacturing paradigm; second, it is predicted to have far-reaching geopolitical and economic implications; and third, it is predicted to have significant environmental benefits.

Additive Manufacturing Paradigm Shift.

The paradigm shift from conventional manufacturing to AM has already begun. In conventional manufacturing, the rule is to optimize a part for manufacturing, whereas with AM, designers can instead optimize a part for its intended function (Winnan, 2012). With traditional manufacturing, a part must be designed for a mold or to be milled or machined. This typically means there will be more upfront capital costs to design and manufacture molds, more scrap material resulting from milling or machining, or both. With AM, a part can be designed the first time to the required specifications without the need to consider molds, milling, or machining (Garrett, 2014:71).

Geopolitical Implications.

In addition to changing the traditional design and manufacturing paradigm, AM is expected to have far-reaching geopolitical implications. One of the predicted political implications of AM is a shift of power from inexpensive manufacturing hubs to design centers (Campbell & Ivanova, 2013:70). In the United States, this may reduce the number of jobs outsourced to countries overseas with the lowest labor costs (Bourell, Leu, & Rosen, 2009:84). Additionally, AM is predicted to impact global trade as it enables localized production, rather than traditional, centralized production and its requisite supply chain and product distribution system. Thus, in the future, global trade may be more tailored to transporting digital designs rather than physical products (Garrett, 2014:71).

Economic Implications.

Future AM proliferation may also shift geopolitical trade and create a significant economic impact. One estimate claims that the AM industry will produce over $5 billion of products and services by 2020 as shown in Figure 1 (Wohlers, 2011:55). Another, more recent study of the industry predicts that the AM market will swell to $21 billion by 2020 (Krauskopf, 2014). With AM, producing one item for which the design already exists is nearly as inexpensive as producing many. Therefore, AM is challenging the long-held concept of economy of scale. This fundamental change in manufacturing is predicted to have vast economic impacts (McNulty, Arnas, & Campbell, 2012:5). Additionally, AM is a significant boon to the "just-in-time" industry practice. With AM, not only can products be delivered just in time, they can now be produced as they are ordered, even further reducing warehousing and logistics requirements (Campbell & Ivanova, 2013:69).

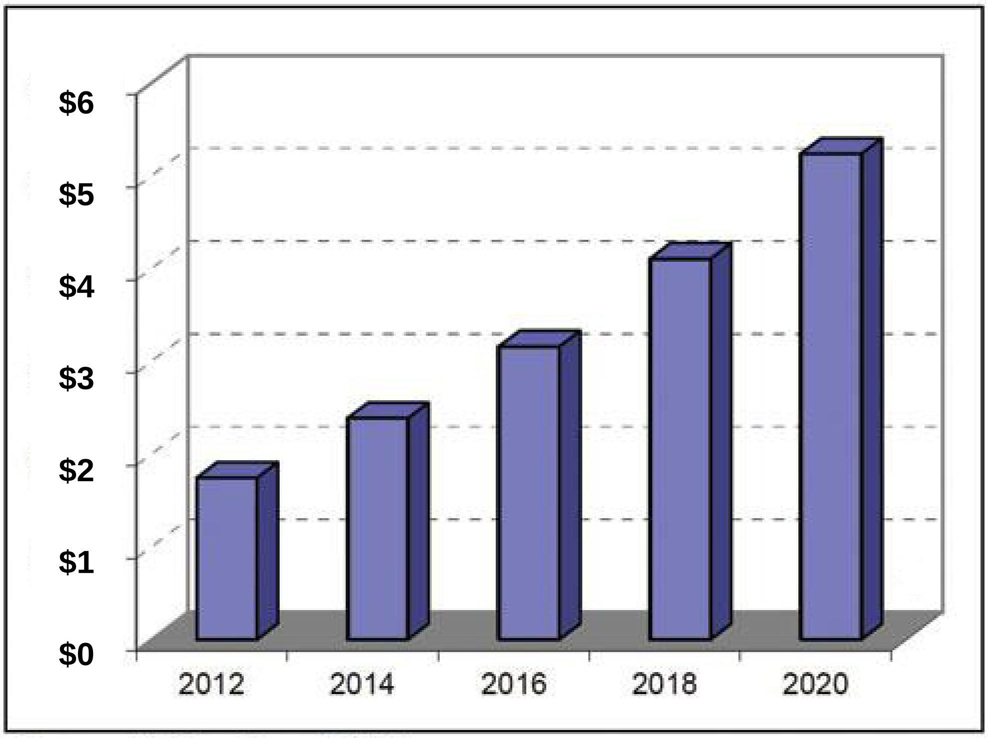


Figure 1. Prediction of Additive Manufacturing Product and Services Revenue in Millions of Dollars (Wohlers, 2011:55)

Environmental Benefits.

In addition to being an economically advantageous manufacturing technique, AM is also expected to be environmentally beneficial. These environmental benefits arise from the additive nature of the process, possibilities for reduced transportation, and a reduction in manufacturing energy requirements. Because AM is an additive process, it is expected to substantially reduce waste compared to traditional subtractive manufacturing (McNulty, Arnas, & Campbell, 2012:5). In fact, AM has been dubbed a "nearly zero waste" process (Garrett, 2014:72). Additionally, AM may increase the "near sourcing" of goods by providing inexpensive manufacturing options at the point of use for items that are traditionally manufactured elsewhere and shipped to the point of use.

Through near sourcing, AM is expected to reduce the amounts of global shipping and air cargo requirements for manufactured goods (Manners-Bell, 2012:3). Finally, AM has been predicted to reduce the overall requirements for energy use in manufacturing although "energy savings are product-specific and vary extensively" (McNulty, Arnas, & Campbell, 2012:6). Nevertheless, it is predicted that AM will contribute to an overall reduction in manufacturing energy use and carbon emissions (Garrett, 2014:72). Because of the predicted environmental benefits of reduced waste, diminished transportation costs, and decreased manufacturing energy use, the AM industry is considered to be truly "environmentally-friendly" (Campbell, Williams, Ivanova, & Garrett, 2011:4).

Military Applications for Additive Manufacturing.

Due to the disruptive nature of AM, the benefits and possibilities it presents have not been overlooked by the United States military services. Significant research is being conducted by the services and other military-sponsored organizations. A few of the ongoing Army, Marine, Navy, and Air Force AM research efforts and applications are reviewed in this section.

The Army began researching AM in the 1990s, looking at stereolithography (Zimmerman & Allen, 2013:13). One of the most interesting, recent applications that the Army has employed is the mobile Expeditionary Labs (Ex Labs), which were delivered to the Rapid Equipping Force in 2012. These Ex Labs contain an AM machine along with traditional manufacturing equipment and are rapidly deployable to forward operating locations to provide custom engineering and prototyping (United States Army Rapid Equipping Force, 2014).

The United States Marine Corps has also been actively pursuing AM technology. A 2014 report outlined several AM applications for the Marines, including inventory reduction capabilities, reduction in transportation costs, and reduction in manufacturing costs (Robert W. Appleton & Company, Inc., 2014:25). These are the same benefits that appeal to many military individuals and organizations.

The US Navy has taken the lead in AM research and has various projects that include AM machines. The recent "Print the Fleet" workshop the Navy held at Dam Neck, Virginia, illustrates the importance the Navy is placing on AM. This workshop was designed to "introduce 3D printing and additive manufacturing to Sailors and other [Navy] stakeholders" (Stinson, 2014). Additionally, the Navy is now utilizing AM machines in all four of its shipyards for rapid prototyping and custom part fabrication (Cullom, 2014). The Navy is also experimenting with AM at sea and has installed AM machines on the USS Essex (Cullom, 2014) and the USS Enterprise (Campbell & Ivanova, 2013:74).

Finally, the Air Force is researching possibilities for the application of AM. Currently, the Air Force employs AM for "design iteration, prototyping, tooling and fixtures, and for some noncritical [aircraft] parts" (Mack, 2013). Recently, the Air Force awarded several multimillion-dollar contracts that use AM for both research and production, including one contract for F-35 parts (3DSystems, 2012) and another for rocket engine parts (Leopold, 2014).

Additive Manufacturing in Contingency Locations.

Additive manufacturing provides a highly customizable and self-contained manufacturing process. As such, it has been considered for application in remote, isolated, and austere contingency environments as a means of producing necessary items while minimizing warehousing requirements. Contingency applications are currently being researched by the Department of Homeland Security, the National Defense University, and the US Army and Navy.

The Department of Homeland Security is assessing the possible applications for AM machines in disaster response scenarios. They are currently evaluating the possibilities for deploying AM machines to a disaster location and providing a central library of digital 3D models that can be physically produced anywhere as needed (Lacaze, Murphy, Mottern, Corley, & Chu, 2014). Additionally, The Center for Technology and National Security Policy at National Defense University has recognized the potential for AM application in contingency environments. As a result, the center recently issued a challenge to "examine the uses of additive manufacturing for humanitarian assistance and disaster relief operations" (McNulty, Arnas, & Campbell, 2012:11).

Furthermore, the US Army has recognized the benefits of using AM in deployed locations. As previously noted, the Army forward deployed AM machines in their Ex Labs in 2012 (United States Army Rapid Equipping Force, 2014). Finally, the Navy is researching the use of AM machines in contingencies on the open seas. They are currently testing the benefits of AM machines deployed on the USS Essex (Cullom, 2014) and the USS Enterprise (Campbell & Ivanova, 2013:74), as previously discussed. These applications show that testing and researching AM application in contingency environments is moving forward and many organizations already recognize the benefits that AM machines can provide in unique situations.

Summary

This chapter has reviewed AFCE UTC utilization and management, current AM technologies, and the current state of the AM industry. This information is provided as a background to the research conducted for this thesis document. The following chapter, Chapter III, will build upon this information and present the methodology utilized in this research.

III. Methodology

This chapter presents the methods and procedures used in this research to determine the suitability of AM for use in AFCE deployment toolkits, or UTCs. To make this determination, a panel of experts was assembled for a Delphi Study. This chapter describes the Delphi method and its application in this research. The results of this study are presented in Chapter IV.

The Delphi Method

The Delphi Method was created out of necessity in the early 1950s. The need for the methodology arose from the RAND Corporation's work on a US military project (Linstone & Turoff, 2011). During this project, significant amounts of forecasting for previously unstudied topics were being undertaken. To ascertain the most accurate predictions, the RAND Corporation turned to leading experts in the field in an effort to gain valuable insight. RAND solicited input from these individuals in several, anonymous rounds and consolidated the varied insights in their report. This was the first research to utilize what would come to be known as a Delphi study.

Delphi Strengths.

The Delphi approach was named after the Oracle at Delphi, a prominent figure in ancient Greek mythology who "was able to predict the future with infallible authority" (Clayton, 1997:374). The name is fitting as a Delphi study is often used to predict the future or to "address what could/should be" (Miller, 2006:1). This stands in contrast to a traditional survey that is designed to understand or represent "what is" (Miller, 2006).

Although the Delphi technique is not a statistical method for creating new knowledge, it is a powerful tool for making the best use of available information (Powell, 2003:380). The Delphi technique is well suited to determining or developing possible program alternatives and to collecting informed judgments on a topic that spans a range of disciplines (Delbecq, Ven, & Gustafson, 1975:11).

The Delphi technique is a good tool for use when planning for the future and looking at program alternatives. This technique is specifically designed to “predict or forecast future events and relationships in order to make appropriate and reasonable plans or changes” (Ludwig, 1997). This is often the case in emerging industry or when applying a new technique in a novel application. In such a situation, the Delphi method excels at predicting future possibilities as it provides a “flexible and adaptable tool to gather and analyze the needed data” (Hsu & Sandford, 2007:5).

The Delphi technique is also beneficial for garnering expert judgment in a multidisciplinary topic. The technique is specifically designed to “gather information from those who are immersed and imbedded in the topic of interest and can provide real-time and real-world knowledge” (Hsu & Sandford, 2007:5). Again, this is particularly useful in emerging technologies and their novel application. Because the Delphi method relies upon targeted experts rather than random individuals, a Delphi study is designed to combine the knowledge and opinions of the participants and to structure and organize their communications (Keeney, Hasson, & McKenna, 2006:206) in an area of uncertainty or where empirical evidence is lacking or yet to be created (Powell, 2003:376-377).

The Delphi technique is a unique tool, suited to unique research applications. In particular, it is a powerful method for forecasting future alternatives and possibilities and for gathering cutting edge, real-time and real-world expert opinions. Although this method differs from more traditional survey or statistical based methodologies, it is a powerful tool when appropriately applied to predictive research.

Delphi Examples.

In reviewing the literature for this thesis, two examples of Delphi studies that exhibit the benefits describe above were discovered. These examples show the beneficial application of the Delphi technique in research similar to this thesis but in different fields. The first example is in the biomedical field and the second is in the mental health field.

In 2012, researchers were studying the possibility of integrating traditional Chinese medical (TCM) practices into Western biomedicine. A Delphi panel was convened to develop policy for this research. This research was able to successfully combine experts from two disparate medical fields and pool their opinions for applying TCM in the biomedical field, illustrating the power of the Delphi technique for combining expertise in a multidisciplinary topic (Chung, Ma, Lau, & Griffiths, 2012).

A second Delphi research study was conducted in 2001 in the mental health field. This research also utilized a Delphi study, which consisted of panel members who were in unrelated fields, to forecast future possibilities. In this study, mental health counselors and computer technologists were combined into a Delphi panel to determine the benefits and possible applications of computer technology in mental health counseling. This study also successfully demonstrated the ability of the Delphi study to bring together two disparate groups of experts to study a topic that spaned both fields (Cabaniss, 2001).

Delphi Features.

Four main features characterize the Delphi method: anonymity of participants, iteration, controlled feedback, and statistical aggregation of group responses (Skulmoski, Hartman, & Krahn, 2007). The first feature, anonymity, encourages participants to share candid opinions. This is important so the broadest possible viewpoints can be solicited and incorporated into the study. The promise of anonymity also encourages respondents to answer without fear of retribution.

Second, a Delphi study is conducted in multiple rounds. The researcher initially crafts questions based on a thorough review of the existing body of knowledge about the topic of interest. A series of questions is then carefully crafted and distributed to the Delphi participants, typically via a questionnaire. Once completed, the participants return their answers to the researcher, who consolidates responses. Aggregated responses are then used as a basis to draft the questions for the next round, which are again sent to the purposive sample of experts. This process is repeated until an end state is achieved in which the responses are stable and further changes do not appear likely. At that point, final results are analyzed. The diagram shown in Figure 2 illustrates this iterative process.

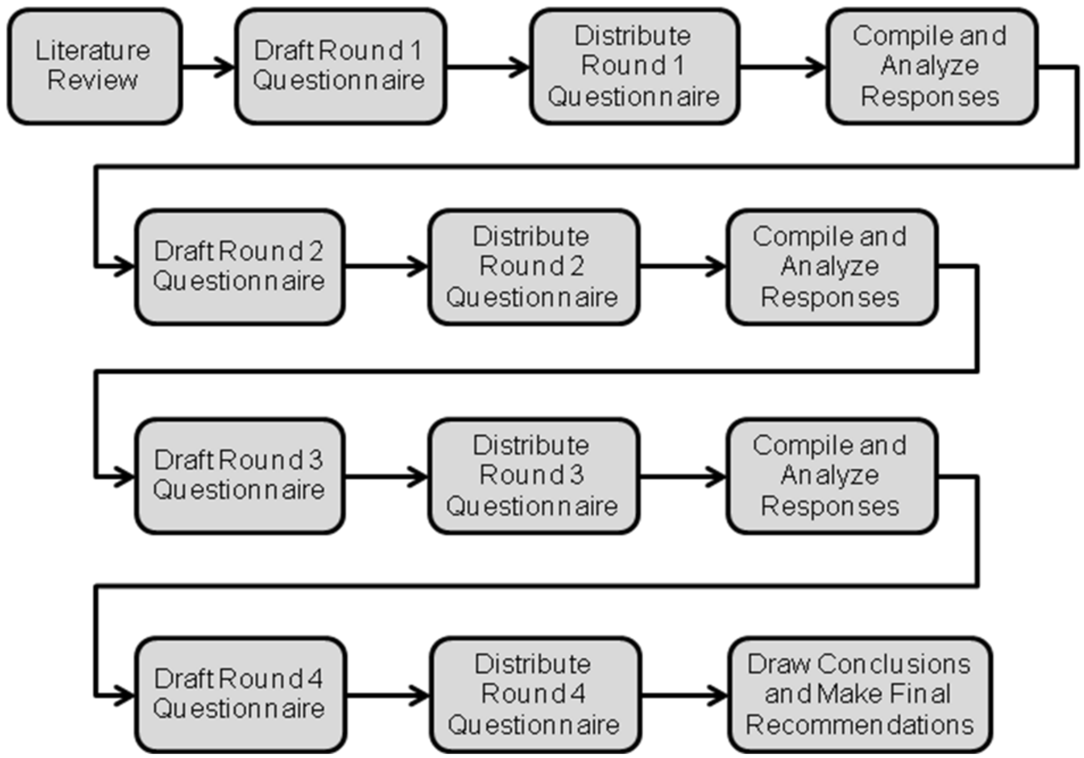


Figure 2. A Four-Round Delphi Method Process.
Adapted from (Skulmoski, Hartman, & Krahn, 2007)

Third, controlled feedback is provided to participants in each round. At the beginning of each round, new questions—along with pertinent responses from the previous rounds—are distributed to the panel members. This serves two purposes. First it ensures accuracy of the researcher's consolidation, and second, feedback provides participants the opinions of the group to stimulate further thought and consideration in future rounds.

Finally, a true Delphi study uses statistical aggregation to interpret the responses of the group. This analysis enables systematic scrutiny of the responses received in the study (Skulmoski, Hartman, & Krahn, 2007). Often, this analysis is performed to determine opinions within the group. In most Delphi studies, once statistical stability is obtained, the Delphi study can be concluded and no further rounds are required.

Delphi Method Considerations.

Several authors have previously determined the aspects of the Delphi study that warrant careful scrutiny during the creation and application of such a study (Landeta, 2006; Skulmoski, Hartman, & Krahn, 2007; Linstone & Turoff, 2011). Each of these articles highlights several key considerations when utilizing a Delphi study. The most important of these considerations are the criteria for selection of experts for the panel and panel size, length and scope of questions asked, pilot application or testing, the number of rounds to be conducted, and methods for encouraging continued participation by study participants.

First, when preparing to conduct a Delphi study, the research should consider the desired composition of the Delphi panel. Of primary concern is the number of experts required for the study. Proper application can be possible with as few as eight members or as many as three hundred or more (Skulmoski, Hartman, & Krahn, 2007). Additionally, the criteria for selection of members must be considered. Because the Delphi study does not utilize random selection of participants, careful scrutiny must be applied when selecting members to cancel bias.

Second, the researcher must carefully craft the questions to be asked during the study. One of the main decisions to be made is the scope of the questions. Would open-ended questions be preferred or would pointed, succinct answers better suit the needs of the research? Typically open ended questions are utilized in early rounds of the Delphi study for idea generation and more pointed questions are asked in later rounds to help focus the group's thinking. The type of questions to be used must be determined during the early stages and reassessed before each phase to maximize the effectiveness of the

Delphi study (Skulmoski, Hartman, & Krahn, 2007). Additionally, the amount of time required to answer each question should be considered. This is often accomplished via a pilot study or pre-test of the questionnaire.

Whether or not to conduct such a preliminary check is the third point on which a researcher should deliberate before utilizing the Delphi method. A pilot study or pre-test will allow the researcher to check the validity and clarity of the questions crafted before submitting them to the panel. It will also provide insight into the expected response time, which the researcher can then manipulate if necessary and use the resultant time as a suggestion for panel members when delivering the questionnaire.

This pilot study also serves as a check to ensure ample care was taken to avoid bias. When drafting the questionnaire for each round, each of the questions were presented to other researchers for review prior to distribution to the panel. These reviewers assessed the questions for readability, clarity, and bias. Further, the questions and statements in Rounds 2 and 3 were primarily drawn from the responses provided from panel members in previous rounds of the study. This was done to limit input by the Delphi facilitator and to decrease bias. Although it is impossible to completely remove bias in a Delphi study, these efforts were considered ample to remove bias for this research.

Finally, it is of critical importance to envisage how to keep panel members engaged and encourage their continued support of the study. Long surveys and lengthy responses will be difficult for panel members to complete, especially as the Delphi panel usually consists of experts who are likely very busy. Often it is necessary to limit the number of questions and rounds utilized in a Delphi study to encourage continued participation (Landeta, 2006). An additional factor that has been found to increase participation and promote enthusiasm from Delphi members is ensuring a quick turnaround between rounds (Skulmoski, Hartman, & Krahn, 2007). This further enables a short duration for the entirety of the study, keeping it fresh in the minds of participants, which promotes continued participation.

Delphi Study Application

The primary method used in this research is a Delphi study. This study was designed to elicit opinions and predictions from a panel of experts who are knowledgeable about AM and/or CE UTCs. To conduct the study, four rounds of questionnaires were distributed to the panel participants via electronic mail. The questionnaires in each round were tailored to generate panel discussion about possible AM applications for CE UTCs. Further, each round built upon answers from the previous rounds. In this section, the panel participants and the study itself are described in greater detail.

Delphi Study Participants.

This Delphi study began with the selection of panel participants. The panel consisted of 20 individuals. Each of these individuals was hand selected based upon past experience and specialized knowledge. Two groups of ten individuals were selected for inclusion in the panel, ten as AM experts and ten as CE UTC experts.

The first group of members selected consisted of ten AM experts. These panel members were chosen from members of the America Makes organization. America Makes is an organization based in Youngstown, Ohio, which aims to "accelerate the adoption of additive manufacturing technologies in the U.S. manufacturing sector and to increase domestic manufacturing competitiveness." Its members are individuals who "are at the forefront of new 3D printing materials, technologies and education" (America Makes, 2014). Delphi participants for this research were chosen from America Makes members based on their experience in academia or industry. Each participant selected was required to have a minimum of 5 years of experience in AM and a working knowledge of various types of AM processes and their respective capabilities and limitations. Table 3 presents the demographics of these AM experts.

The second group of Delphi panel members was selected for their experience in CE UTC use and management. These members were selected from members of the Air Force Civil Engineer Center (AFCEC). AFCEC is the Air Force organization responsible for the planning and policy for all CE UTCs. Therefore, the individuals selected for this Delphi study were selected from the AFCEC personnel who are responsible for UTC plans and policies. Panelists were required to have a minimum of 3 years of experience managing or creating policy for CE UTCs and a working knowledge of CE UTC contents and requirements. Table 3 also presents the demographics of these UTC experts.

Table 3. Delphi Panel Demographics

	AM Experts	CE UTC Experts
Number of Panelists	10	10
Gender	100% Male	90% Male / 10% Female
Age	38 – 73	35 – 45
Years Experience	5 – 23	10 – 23
Education	Associates Degree – 10% Bachelor of Science – 0% Doctor of Philosophy – 50% No Response – 40%	Associates Degree – 30% Bachelor of Science – 50% Doctor of Philosophy – 0% No Response – 20%

Conducting the Delphi Study.

To gather data for this research project, a Delphi study was conducted with the individuals described in the previous section. This study was conducted in four distinct rounds. Each of these rounds is discussed in this section.

Before the first round of this Delphi study was conducted, a literature review was performed to determine the current state of the AM industry and to understand the current methods for deploying CE UTCs. This information is presented in Chapter II of this thesis. This background information was used as a starting point for the first round of the Delphi study.

One objective of a Delphi study is to determine if consensus exists among panel members. Therefore, it is important to define what will constitute consensus for this study. Although varying levels of consensus are used for Delphi studies (Powell, 2003:379), for this research, consensus will be determined in one of two ways: either as 75% or more of respondents being in agreement or as determined by the mean of statistically aggregated responses. The 75% value is suggested in the literature as it constitutes more than a simple majority but is not so strict as to require 100% consensus (Keeney, Hasson, & McKenna, 2006:210). In other cases, the mean value will be used to determine panel consensus as it is a measure of central tendency, which will indicate what the majority of respondents believe (McClave, Benson, & Sincich, 2011:57). Additionally, the mean score is appropriate because it is sensitive to extreme responses or responses where only one panel member disagrees with the majority of the panel. This will provide an indication of disagreement when compared with the median responses, which are less sensitive to extreme values (Anderson, Sweeney, & Williams, 1999:67).

Another goal of a Delphi study is to achieve stability in panel responses. Stability indicates that the panel has sufficiently deliberated on the topic and each member has come to an ultimate conclusion, whether perfect consensus is reached or not. This stability will be evident when the point of diminishing returns is reached such that no new information is attained in subsequent rounds (Keeney, Hasson, & McKenna, 2006:207).

In Round 1 of this study, a questionnaire was created, which consisted of open-response and multiple-choice questions. This questionnaire was designed to gather opinions from each of the panel members concerning AM machine integration into CE UTCs. Specifically, the questionnaire was designed to elicit responses that would answer the investigative questions of this research. The investigative questions that were the basis for the Round 1 questionnaire are:

1) *What categories of AM machine are currently well suited for utilization in CE equipment UTCs?*
2) *What attributes make an AM machine well suited for use in a CE equipment UTC?*
3) *Has the AM industry currently reached a point at which the selected categories of AM machines embody these beneficial attributes?*

Each of the questions in Round 1 stems from these three investigative questions. The Round 1 questionnaire is presented in Appendix A of this document.

After the questionnaire was drafted, it was distributed to the panel members via electronic mail (e-mail). Respondents were initially given one week to respond but responses received later were also accepted and are included in this research. Finally, the responses received from each member were compiled and sorted into common categories.

To determine common categories of answers among respondents, qualitative analysis is used to code the responses received. The purpose of this analysis is to "transform data into findings" (Patton, 2002:433). The responses received were reviewed and categorized into one of several categories that "symbolically assign a summative, salient, essence-capturing, and/or evocative attribute for a portion of language-based…data" (Saldana, 2009:3). The total number of responses that were determined to fall into each category was then tallied. The responses for several questions were also presented to other researchers for validation and to certify intercoder reliability. This validation was performed for no less than 10% of the data, as suggested in the literature (Lombard, Snyder-Duch, & Bracken, 2002:601).

Round 2 of this Delphi study began with an analysis of the common themes found in the previous round. These themes were used as a basis in designing the questionnaire for Round 2. The questions in this round aimed to clarify and validate the responses received in Round 1. The Round 2 questionnaire consisted primarily of "Likert-based" questions. Likert questions were first designed in 1932 to measure the attitudes of respondents (Likert, 1932) and are now a "well-accepted technique for attitude measurement" (Klooster, Visser, & Jong, 2008:513). These questions simplify participants' responses to numerical values that are more easily analyzed to determine consensus among panel members. The questionnaire developed for Round 2 of this Delphi study is presented in Appendix B.

In phase two of Round 2, both the questionnaire and the results from the previous round were emailed to panel members. Again, responses from this round were compiled, coded, and analyzed. The results from this round were primarily numerical. For these numerical questions, simple statistical metrics (i.e., mean, median, mode, and percentage) were calculated and are ample for analysis (Hsu & Sandford, 2007:4). After the results were analyzed, Round 2 was concluded.

In Round 3 of this Delphi study, a questionnaire was drafted to determine a final forecast. The responses and themes from the first two rounds of this study were reviewed and ten statements of the committee members' combined opinions were drafted. A Likert scale was then created for each statement to determine the final opinions of the panel members for each topic. The Round 3 questionnaire is presented in Appendix C. The questionnaire was distributed to panel members and responses were once again consolidated. Simple statistical measures were again considered for each question (i.e., mean, median, mode, and percentage).

One final round of this Delphi study was then conducted. The questionnaire for Round 4 consisted of only three questions and is presented in Appendix D. These questions were designed to ensure final stability of Delphi panel opinions and to solicit any final comments. These results were compared with those from the previous rounds and it was found that little new knowledge was gained. Thus, the "point of diminishing returns" was reached and therefore there was no reason to conduct any further rounds of this Delphi study (Keeney, Hasson, & McKenna, 2006:207). Accordingly, the Delphi portion of this research was concluded.

Box Plots

To convey the information obtained in the Delphi study, box plots were created for each of the applicable responses. Box plots are an exploratory data analysis tool for visually presenting data; these plots are designed to show the central tendency of data and "to rapidly summarize and interpret tabular data" (Williamson, Parker, & Kendrick, 1989:916). For this research, the box plots are included to show the amount of agreement or disagreement among panel members.

To construct a box plot, four descriptive statistics were calculated for each set of Likert values. To calculate these numbers, the Likert items were first sorted numerically from lowest value to highest value. Then the four requisite statistics were calculated, namely 1) the median, the middle value if there are an odd number of data points or the average of the two middle values if there are an even number of data points; 2) the interquartile range (IQR), which encompasses the middle 50% of data points in the set; 3) the *H*-spread, which encompasses all data points that fall within 1.5 times the IQR; and 4) outliers, any data points that fall outside the *H*-spread. The box plot was then generated by graphically constructing a vertical box representing the IQR with a horizontal line through the box at the median value. The *H*-spread is depicted by drawing vertical lines above and below the box, which stop at the largest and smallest data values inside the *H*-spread. Lastly, any outliers are depicted on the plot by placing an asterisk above or below the *H*-spread (Williamson, Parker, & Kendrick, 1989:919)

For this research, two separate box plots were created for all questions that have Likert based responses. The first box plot includes the data points generated from the responses provided by UTC experts. The second box plot was generated based on the data from AM expert responses. These box plots were placed side by side so the responses from these two diverse groups of respondents can be visually compared.

Institutional Review Board

This research contains a Delphi study that, by its nature, involves working with human subjects. Therefore, the research is subject to the oversight of the Institutional Review Board (IRB) as required by the Code of Federal Regulations (CFR), Title 32, Part 219. The purpose of this oversight is to protect the individuals involved in the study and their rights. Specifically, the individuals are to be protected from reprisal or from damage to their financial standing, employability, or reputation. Additionally, this oversight ensures that Personally Identifiable Information (PII) for these individuals is protected and not inadvertently released (32 CFR 219.101, 2014).

At the beginning of this research, a plan for the study was presented to the IRB for review. This plan outlined the method for protecting the rights of the individuals who participated in the study and the manner in which their rights and PII would be safeguarded. The IRB reviewed this plan and made a determination that the research was exempt from human experimentation requirements as defined in 32 CFR 219 paragraph (b) (2) on 31 July 2014. This determination is included in Appendix E.

Summary

This chapter has presented the methodology utilized in this research to provide insight into the significant factors that will determine the applicability of AM machines in CE UTCs. The Delphi study conducted for this research and the participants in that study were described. The results of these methods are presented in Chapter IV.

IV. Analysis and Results

The preceding chapter presented the research methodology utilized in this thesis. The methodology primarily outlined the process for conducting a Delphi study designed to determine how the inclusion of AM machines would be beneficial in Air Force CE UTCs and to predict the appropriate timeframe for their inclusion. The Delphi study as described in Chapter III was conducted between August and December of 2015. The results of each round of this study and an analysis of these results are presented in this chapter.

Delphi Study Results

For this research, a four-round Delphi study was conducted as described in Chapter III of this thesis. The questionnaires for each of these rounds and the results of the responses received are presented below. Additionally, an analysis of the results is presented for each round.

Round 1.

In Round 1 of this Delphi study, eight questions were posed to the panel concerning AM technology and CE UTCs. Five of these questions were multiple-choice and three were open-response. Appendix A presents the questions that were included in the first round of the Delphi study.

After the first-round questionnaire was distributed, responses were received and compiled from panel members. In Round 1, 16 responses were received from the 20 questionnaires distributed.   Ten of the respondents were UTC experts and six were AM experts as shown in Table 4. The responses were then aggregated to determine the percentage of panel members who chose a specific answer for each question. The results for questions one through five were analyzed thus and are presented in Table 5.

Table 4. Delphi Round 1 Participation

Questionnaires Distributed	**20**		**Percentage of Responses**
Responses Received	Total	16	100
	UTC Experts	10	63
	AM Experts	6	37

Table 5. Delphi Round 1 Results Questions 1 – 5

1) What qualities of an AM machine would make it well suited for use in a CE UTC or in a deployed or field operating environment?

AM Machine Quality	Percent of 16 Respondents
Usability	75
Reliability	63
Adaptability	63
Flexibility	56
Quality	50
Safety	31
Interoperability	13
Resilience	6
Other	0

2) Which categories of AM machines show potential to endure many years into the future?

AM Machine Category	Percent of 12 Respondents
Powder Bed Fusion	67
Directed Energy Deposition	58
Material Extrusion	50
Binder Jetting	42
Material Jetting	25
Vat Photopolymerization	17

3)	Do you think AM technology has currently reached a point where including an AM machine in a UTC would be beneficial?

Yes or No	Percent of 16 Respondents
Yes	38
No	62

4)	When do you think technology will progress far enough that inclusion would be beneficial?

Time Range	Percent of 9 Respondents
1-5 Years	45
5-10 Years	33
10-15 Years	11
15+ Years	11

5)	Which types of CE UTCs could be most benefited by inclusion of an AM machine?

Time Range	Percent of 15 Respondents
Light Construction	67
Heavy Construction	40
Surveying	40
Construction Admin	33
Explosive Ordinance Disposal	33
Other	20

Question one of this round asked what qualities of an AM machine would be desirable for CE UTC applications. The results from this study show that the Delphi panel members consider usability to be the most important quality for a deployed AM machine. This quality was identified by 75% of the Delphi participants as being important. Additional desirable qualities that were identified are reliability, flexibility, and adaptability. Although these qualities did not meet the 75% consensus criterion, they were tied for secondary importance, and more than half of the panel members citied them as important. Finally, quality and safety were also identified by at least one-third of the respondents as an important quality. Because of their popularity among panel members, these six qualities were identified as candidates for further discussion in Round 2.

In question two, the respondents were asked to identify categories of AM machines that would endure into the future. The categories from *ASTM F-42 Classification of Additive Manufacturing Processes* (ASTM International, 2012) were used as a basis for the responses to this question. The panel members were divided in their opinions on this question, and no process stood out as being most enduring. However, the most common responses were—in order of frequency—powder bed fusion, directed energy deposition, material extrusion, and binder jetting. These processes were identified by five or more respondents, which constitutes one-third of the panel members. Therefore, these four processes were identified for further discussion.

Questions three and four of the first round of this Delphi study attempted to determine the time frame in which including an AM machine in CE UTCs is expected to be beneficial. Of panelists who responded, 88% agree that including an AM machine would be beneficial within the next 10 years, which constitutes consensus. Further, 38% of respondents agree that doing so would be beneficial today.

Question five of the first round of this Delphi study was designed to determine the appropriate CE applications for a deployed AM machine. The results of this question identify that an AM machine would be best suited for light construction applications such as those the 4F9ET UTC is designed for. Almost 65% of respondents identified this as the appropriate application for a deployed AM machine. Four other noteworthy applications were identified by over 25% of the panel members: heavy construction,

construction administration (such as project management and oversight), explosive ordnance disposal, and surveying. Although consensus was not reached for any of these applications, these five categories were identified as the most important and were selected for further panel discussion.

The first five questions in Round 1 of this Delphi study were numerically based, but questions six and seven of the Round 1 questionnaire were posed as open-response questions. The panel members' answers for these questions were compiled and then coded to identify common themes in responses as described in Chapter III of this document. The themes discovered for these questions are presented in Table 6 along with the percentage of panel members whose responses included each theme.

Table 6. Delphi Round 1 Results Questions 6 – 7

6)	What are some potential benefits of including an AM machine in a CE UTC?	
	Potential Benefit	Percent of 16 Respondents
	Part production	63
	Rapid/on-demand production	31
	Prototyping/models	25
	Tool production	25
	Reduced inventory	19
	Local production	13
	Better supply chain options	13
	Inexpensive	6
	Construction	6
	Increased UTC capability	6
	Easy to transport	6

7) What are some challenges that may arise from including an AM machine in a CE UTC?

Potential Challenge	Percent of 15 Respondents
Cost prohibitive	53
Currently no added benefit from including	47
Concerns about the characteristics of an AM machine	40
Slower processing than conventional	33
Power supply concerns	27
Product qualities lacking	27
AM machine training challenges	20
New organizational models	20
Raw material problems	13
AM is not just a machine, need other components	13
Software/CAD file availability	13
Production size limited	13
Security	7

The responses from question six were used to determine the most promising benefits of including an AM machine in a CE UTC. The panel members agreed (63% of respondents) that the most important benefit of including an AM machine is the ability to create various necessary parts. Additionally, the panel members identified that the ability for rapid, on-demand production of these parts would be beneficial (31%). Other benefits mentioned multiple times included prototyping and model building, tool production, reduced inventory, and better supply chain options. These seven benefits were selected for further discussion although consensus was not reached for any of these benefits individually in this round.

In addition to identifying the benefits, panel members were asked to identify the possible challenges that may arise if an AM machine is included in a CE UTC. The biggest concern panel members noted is how operator training will be accomplished for the use of a new AM machine. Over half of the respondents were concerned about this matter. Additional concerns were identified about the qualities of an AM machine, the material used in the machine, the availability of the software to run the machine, the cost of the machine, and the power supply for the machine. Each of these concerns was shared by over one-quarter of the Delphi participants. Again, though these were not identified by 75% of the panel, which would constitute consensus, these six challenges were selected for further analysis.

The final question of this round, question eight, was an open-response question. The question asked panel members for any additional comments. In addition, open-responses were solicited for questions one, two, four, five, six, and seven of this round. The results of these open-response comments were included in the interpretation of the results for questions one through seven. The comments provided from these open-responses were also compiled and considered when drafting Round 2 of this Delphi study and these responses are presented in Appendix F.

Round 2.

In Round 2 of this Delphi study, the important, common, and unique results from Round 1 were presented for further discussion. For this round, nine questions were formulated and distributed to the panel. The questions for Round 2 are presented in Appendix B of this thesis.

After Round 2 was distributed, responses were received and compiled from Delphi participants. Fifteen responses were received for Round 2 of this study of the twenty questionnaires distributed. Eight responses were from UTC experts and the remaining seven were from AM experts as shown in Table 7. These responses were aggregated and coded as described in Chapter III of this thesis. The results for questions one through eight are presented in Table 8.

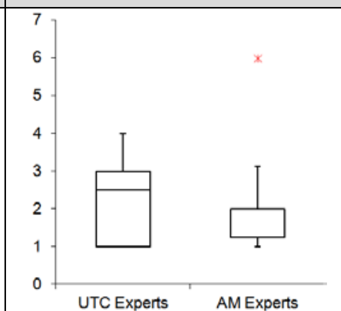
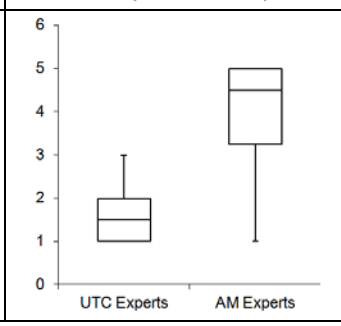
Table 7. Delphi Round 2 Participation

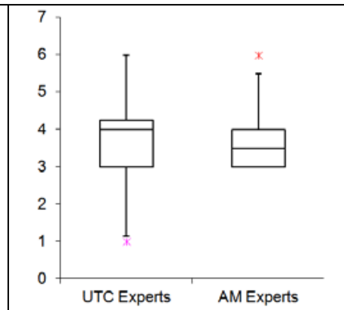
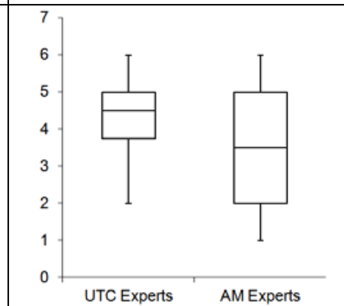
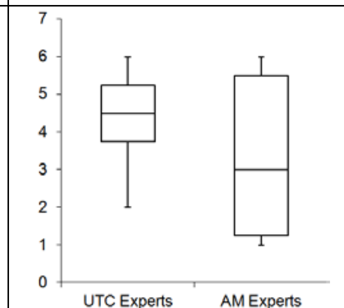
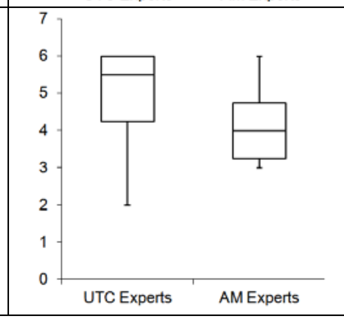
Questionnaires Distributed	20		Percentage of Responses
Responses Received	Total	15	100
	UTC Experts	8	53
	AM Experts	7	47

Table 8. Delphi Round 2 Results

1) After compiling the possible BENEFITS of including an AM machine in a CE UTC, six common themes were discovered among Round 1 respondents. Of these six possible benefits, which do you believe are the most promising for the future of deployed civil engineer operations?

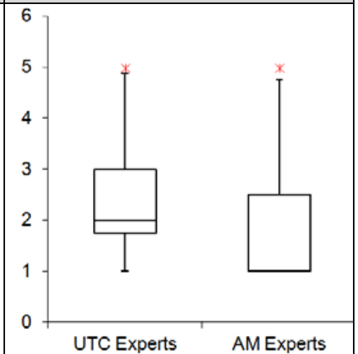
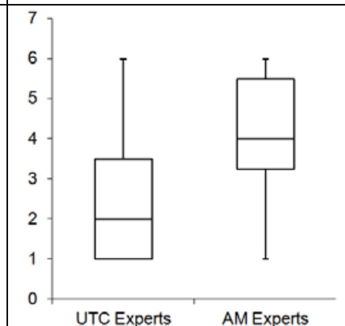
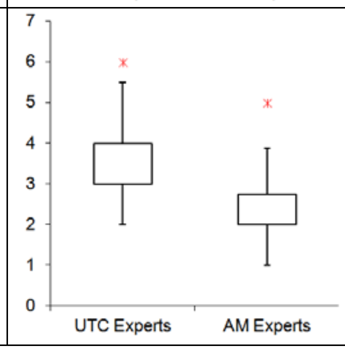
Most Promising 1 2 3 4 5 6 Least Promising

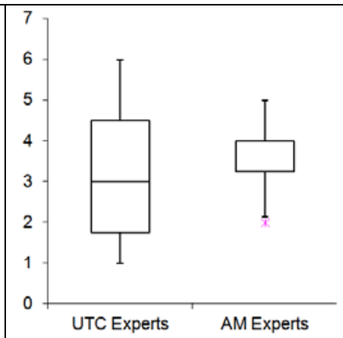
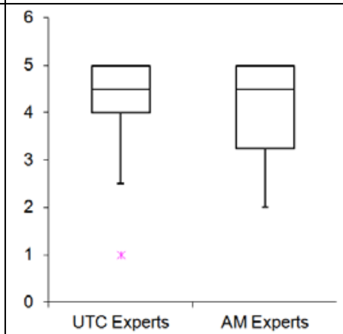
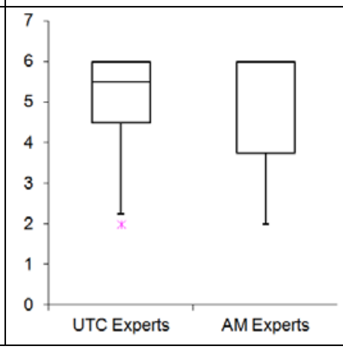
Possible Benefit	Mean Score	Box Plot
AM machines can be used to produce necessary and specialized tools on site	2.3	
AM machines can be used to produce spare parts when needed	2.6	

	AM capabilities can enable a reduction of inventory of parts, tools, etc	3.8	
	AM machines allow on-demand and rapid production	3.9	
	AM machines allow production of prototypes and models on site and in real time	3.9	
	AM machines allow independence from some aspects of a traditional supply chain	4.5	

2) After compiling the possible DRAWBACKS of including an AM machine in a CE UTC, six common themes were discovered among Round 1 respondents. Of these six possible drawbacks, which do you believe are the most important to address before considering AM machines for deployed CE applications?

Most Important 1 2 3 4 5 6 Least Important

Possible Drawback	Mean Score	Box Plot
Raw material concerns, such as sourcing and safety	2.2	
Cost-prohibitive nature of AM machines and materials	3.2	
Careful consideration of AM machine characteristics in a deployed environment	3.2	

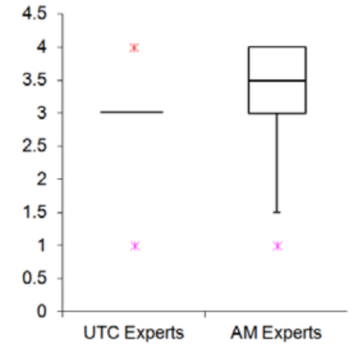
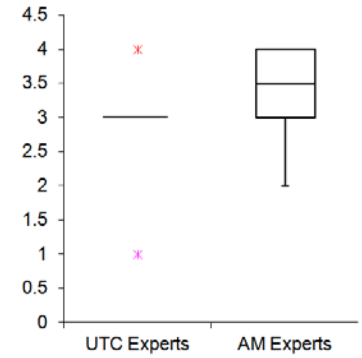
	Training requirements for AM machine operators and users	3.4	
	Availability of necessary software and a “library” of items to produce	4.1	
	Power supply for AM machines	4.9	

3) 80% of Round 1 respondents believe that an AM machine would be useful in at least one variety of UTC; however, no consensus was reached for which type would be best. Do you believe it would be better to:

Option	Percent of 15 Respondents
Include an AM machine in existing UTCs?	23
Create a new, AM specific UTC?	47
Consider other methods for deploying an AM machine?	30

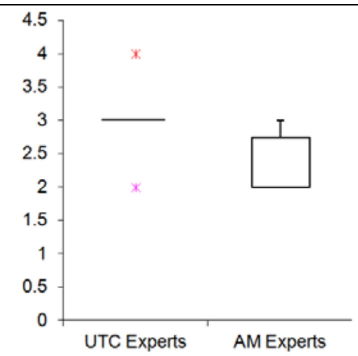
4) How beneficial do you believe inclusion of each of these types of AM machine would be in a CE UTC?

Not at all beneficial 1 2 3 4 Very beneficial

	Mean	Median	Mode	
Plastic/Polymer	2.87	3	3	
Metal	3.13	3	3	

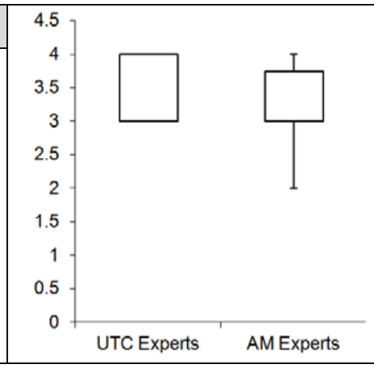
5) How important do you believe it would be to choose an AM machine for CE UTC application that can use locally sourced materials?

Not at all important 1 2 3 4 Very important

Mean	Median	Mode	
2.73	3	3	

6) How important do you believe it would be to include a 3D scanner?

Not at all important 1 2 3 4 Very important

Mean	Median	Mode	
3.33	3	3	

7) In your opinion, would a case study be useful for further determining possible future applications of AM machines in CE UTCs?

Response	Percentage of 15 Respondents
Yes	93
No	7

8) What aspects should be tested and what should be the scope of a pilot or case study if one was to be conducted?

Aspect to Test	Percent of 15 Respondents
Test various AM machines/software in deployed environment	87
Test actual part quality	53
Evaluate AM machine "-ilities"	53
Test training plan	33
Test applicability to current CE requirements	27
Test assumed benefits (from question 1)	27
Test various raw materials	27
Test actual costs	7

In Round 2 of the Delphi study conducted for this research, the panel was asked to clarify the results from Round 1 and respond to additional questions. In particular, questions one and two of this round addressed the benefits and drawbacks, determined in Round 1, of including an AM machine in a CE UTC. From these questions, it was determined that the most promising benefits arise from the ability to produce spare parts and tools with an AM machine in a deployed environment. Concerns about raw material procurement, safety, and availability were identified as the most important to address before implementation. These responses were selected for further discussion as they all scored a mean of 2.0 or lower indicating they were considered most important by the panel.

In Round 2, question three addressed the appropriate method for delivering an AM machine to a deployed location. Three options were presented: including the machine in an existing UTC, including the machine in a new UTC, or considering another method for deployment. Respondents were also provided an open-response section to clarify or further expand upon their answer. Based upon the responses received, it is apparent that the panel believes that a new UTC would be the best option for AM machine deployment. This is clear as almost 50% of the responses identified this option and it was the most commonly selected response.

In question four of this round, the Delphi panel was asked to consider if a metal or plastic/polymer AM machine would be beneficial for CE deployed applications. Panel responses were varied on this topic. It appears that either type of machine would be beneficial, with metal being slightly favored. However, the results obtained are not strong enough to conclude that either type of machine would be better for this application.

Questions five and six ask about the importance availability of locally sourced material and of including a 3D scanner in a deployed AM machine kit. Panelists' responses indicate that these factors are slightly important to consider. The panel determined it is slightly important to include a 3D scanner and the availability of locally sourced materials is slightly unimportant. These factors were discovered in Round 1 of this Delphi study and selected for further discussion. However, based upon responses in Round 2, these issues do not appear to be influential concerns for the overall topic and therefore were not further discussed in the Delphi study.

Questions seven and eight in Round 2 of this Delphi study are related to the creation of a pilot or case study to gather further data concerning the possibilities for AM deployment in CE UTCs. The respondents were almost unanimous (14 out of 15) in affirming the usefulness of such a study, which satisfies the consensus requirements for this research. The panel determined that a case or pilot study should focus on testing various types of AM machines and software in a deployed environment and validating the anticipated results of this Delphi study in such an environment. This opinion was also strong enough to be construed as consensus from the committee. The second-most important factors to study are the “-ilities” of AM machines and the quality of the parts produced by them in a deployed environment. Although fewer than 75% of the panel indicated that these factors should be considered when designing a case or pilot study, more than half agreed they should.

As in Round 1, the final question for Round 2 was an open-response question soliciting additional clarification or final comments from the panel members. The responses from this question were integrated into the results and responses for question one through eight. No analysis was performed on this question individually. Appendix F presents the responses received in this final question.

Round 3.

After the responses were received and analyzed for Round 2, the questionnaire for Round 3 of this Delphi study was created. The questions for this round built upon the findings obtained in Rounds 1 and 2 of this study. The questions in this round, however, were designed to determine the final opinions of the panel on the important topics and findings of this Delphi study. The questions created for this round are presented in Appendix C of this document. In Round 3, participants were asked to rate their response on a Likert scale for the first 10 questions. Possible responses ranged from 1 to 5, with 1 indicating the panel member agreed with the main point described in the question and 5 indicating the member disagreed with the point. The scale was the same for each question and is presented in Table 9.

Table 9. Delphi Study Round 3 Response Scale

Response	Likert Value
AGREE with the main point	1
SOMEWHAT AGREE with the main point	2
NEITHER agree nor disagree with the main point	3
SOMEWHAT DISAGREE with the main point	4
DISAGREE with the main point	5

At the conclusion of Round 3, the responses received from the participants were compiled. In Round 3, sixteen responses were received of the twenty questionnaires distributed (Table 10). The mean, median, and mode for these compiled responses were then calculated to determine consensus among panel members. The results for questions one through ten were analyzed and are presented in Table 11.

Table 10. Delphi Round 3 Participation

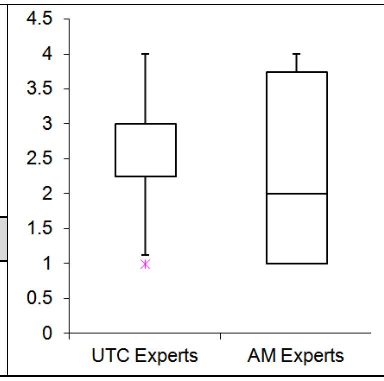
Questionnaires Distributed	20		Percentage of Responses
Responses Received	Total	16	100
	UTC Experts	10	63
	AM Experts	6	37

Table 11. Delphi Study Round 3 Results

AM Machine Capabilities

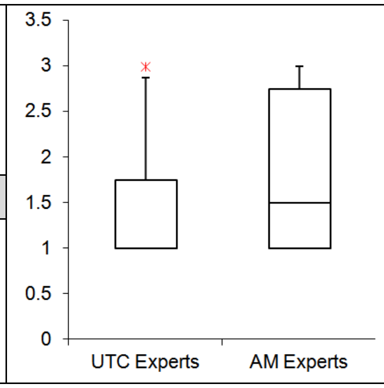
1) The types of AM machine best suited for use in deployed CE operations are Powder Bed Fusion or Directed Energy Deposition machines. Two other promising options are Material Extrusion and Binder Jetting.

Mean	Median	Mode
2.5	3.0	3.0



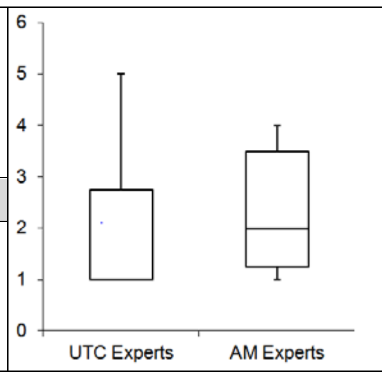
2) The quality of an AM machine most important to consider for deployed CE applications is Usability. Additionally, Reliability, Flexibility, and Adaptability are qualities of secondary importance.

Mean	Median	Mode
1.6	1.0	1.0



3) An AM machine that uses metal raw material is most likely the best option for CE applications but plastic/polymer machines should not be completely ruled out.

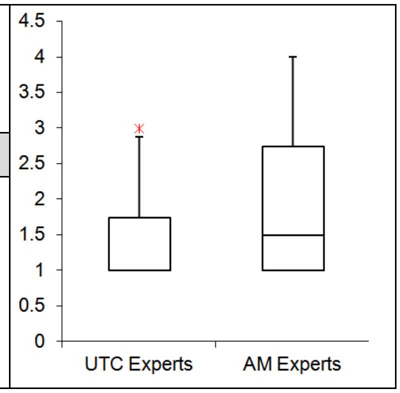
Mean	Median	Mode
2.1	1.5	1.0



Benefits and Drawbacks of AM Machines

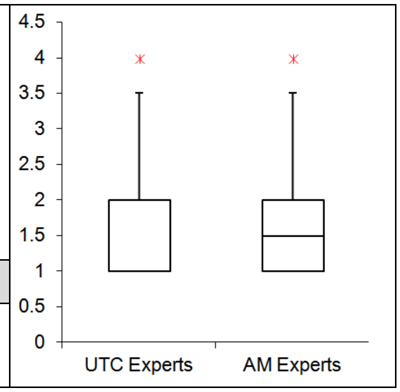
4) The most promising benefit of a deployed AM machine for the CE community is the ability to create specialized tools and parts on site and on demand.

Mean	Median	Mode
1.6	1.0	1.0



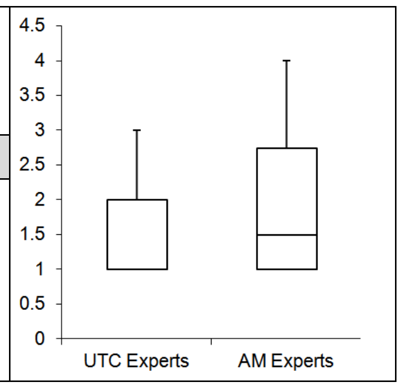
5) The most important drawbacks to address before deploying an AM machine for CE operations are the source, cost, and safety of the raw material for the machine. Additionally, training requirements, machine characteristics, and initial costs are secondary drawbacks that should be addressed.

Mean	Median	Mode
1.75	1.0	1.0



6) To most effectively deploy an AM machine for CE use, a new UTC should be created or another avenue of deployment should be considered.

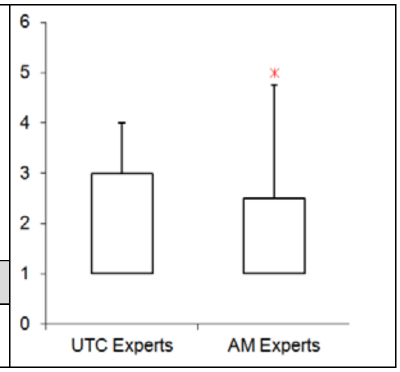
Mean	Median	Mode
1.75	1.0	1.0



Pilot Study

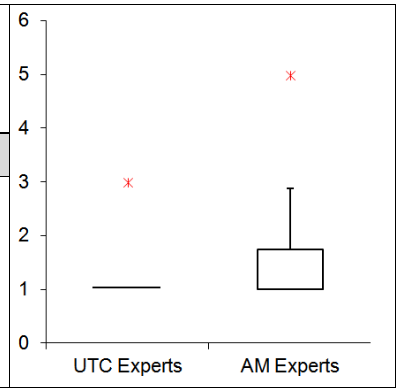
7) Creating a pilot study or case study for AM machine deployment would be very beneficial and technology has progressed far enough that this initial study can be performed today. Within 5 years it is expected that this technology will have progressed enough that full-scale deployment of an AM machine will be beneficial.

Mean	Median	Mode
2.0	1.0	1.0



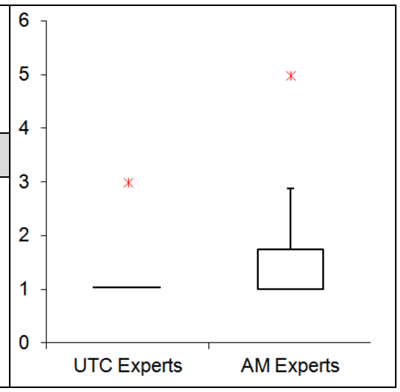
8) This study should primarily be designed to test the ability of an AM machine to meet real world CE requirements in a deployed environment.

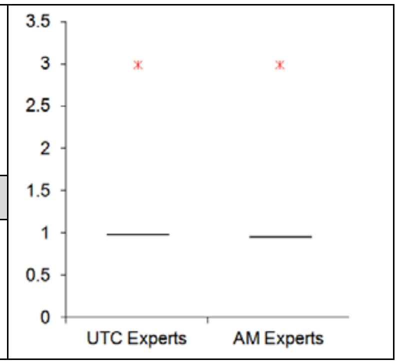
Mean	Median	Mode
1.5	1.0	1.0



9) This study should also be designed to focus on the quality of the parts produced in a deployed environment and their suitability for CE applications.

Mean	Median	Mode
1.4	1.0	1.0



10)	This study should also consider the "-ilities" of an AM machine when used in a deployed environment. These "ilities" include usability, adaptability, reliability, maintainability, etc.			
	Mean	Median	Mode	
	1.3	1.0	1.0	

The questions in Round 3 of this Delphi study can be divided into three categories for ease of analysis: 1) AM machine capabilities, which includes questions 1 – 3; 2) Benefits and drawbacks of AM use in Air Force CE contingency operations, which includes questions 4 – 6; and 3) pilot study questions, which includes questions 7 – 10.

AM Machine Capabilities.

Questions 1 – 3 address the capabilities of additive manufacturing machines. Some dissension appeared among panel members on questions one and three, which address the type of AM machine that should be used for Air Force CE contingency operations. The panel members were not decisive in selecting either the type (Question 1) or material (Question 3) that should be used for this application. Part of this lack of agreement may have arisen due to the dual nature of these questions, which may have created confusion or biased the results of the first part of the question if a panel member did not agree with the second part or vice versa. Regardless, throughout the study there was lack of consensus on these points and these topics have been suggested for further research in Chapter V of this research. Conversely, there was strong consensus among panel members that usability is the most important quality to consider for an AM machine in these operations.

Benefits and Drawbacks of AM Machines.

Benefits and drawbacks of using AM machines for Air Force CE contingency operations were discussed in questions 4-6. The panel somewhat agreed on the responses for each of these questions. First, it was somewhat agreed that the most promising benefit that may be realized by deploying an AM machine is the ability to create parts and tools on site, and on demand. Panel members also somewhat agreed that the most important concerns to address prior to deploying this machine are related to the raw material used for production. It was also somewhat agreed that the most beneficial way to deploy an AM downrange is via a new UTC.

Pilot Study.

Questions 7-10 of Round 3 of this Delphi study were related to a pilot study. The results of Question 7 indicate that panel members somewhat agreed that conducting a pilot study at the conclusion of this research would be beneficial. Further, there was strong agreement among the members about how the study should be designed as shown in Question 8 – 10. These responses indicate that panel members agree that if a pilot study is conducted, it should primarily focus on the actual ability of an AM machine to meet CE needs in a deployed environment. Delphi participants also agreed that this study should be designed to test the "-ilities" of both an AM machine and the parts it produces in a deployed environment.

In addition to the ten Likert questions asked in Round 3, an open-response question was asked at the conclusion of this round. The responses from this question were used as a basis for understanding the responses for the previous 10 questions. No analysis was performed on this question individually and the responses are included in Appendix F.

Round 4.

After the conclusion of Round 3, one last call was sent out to participants to solicit any final comments. The results of Round 3 were distributed to panelists and these individuals were instructed that these results would be the ultimate findings of the study. The Round 4 questionnaire asked three questions to guide discussion and direct responses. 1) Do you feel these statements are an accurate reflection of the committee's opinions? 2) Do you feel these statements include your inputs and opinions? 3) Do you have any final comments? The Round 4 questionnaire is presented in Appendix D.

At the conclusion of Round 4, the responses received were compiled for analysis. In Round 4, only nine responses were received of the twenty questionnaires distributed, seven from UTC experts and two from AM experts as shown in Table 12. Additionally, Table 13 presents a summary of the responses received in Round 4.

Table 12. Delphi Round 4 Participation

<table>
<tr><th>Questionnaires Distributed</th><th colspan="2">20</th><th>Percentage of Responses</th></tr>
<tr><td rowspan="3">Responses Received</td><td>Total</td><td>9</td><td>100</td></tr>
<tr><td>UTC Experts</td><td>7</td><td>78</td></tr>
<tr><td>AM Experts</td><td>2</td><td>22</td></tr>
</table>

Table 13. Delphi Study Round 4 Results

1) Do you feel these statements are an accurate reflection of the committee's opinions?

Response	Percentage of 9 Respondents
Yes	89
No	11

2) Do you feel these statements include your inputs and opinions?

Response	Percentage of 9 Respondents
Yes	89
No	11

Of the responses received in Round 4, a majority (89%) agreed that the responses accurately reflected both the committee's opinions and their own. Although 100% consensus was not achieved, the overall responses are an aggregate of all the participants' beliefs and perfect agreement is not expected. Significantly, this also surpasses the 75% requirement in this research for consensus.

The responses received for the third question were varied. Many of these open-responses were simply comments on the overall study and participants' interest. Other responses highlighted topics already addressed in this study. These responses are presented in Appendix F. However, after analysis, it was determined that no new information was provided and no new topics were presented in the responses to this question. Therefore no analysis was performed on this question individually but the responses to this question were used in the preparation of this thesis.

At the conclusion of Round 4, it was noted that there was a significant decrease in response rate from the previous rounds. Additionally, there were no new comments about the findings of the study received from Round 4 responses. Rather, the responses echoed those provided in Round 3. This indicates that stability had been reached in the panel opinions. Further, it provides evidence that the "point of diminishing returns" was reached in Round 4 of this Delphi study (Keeney, Hasson, & McKenna, 2006:207). As a result, the Delphi study was concluded.

Summary

This chapter has outlined the results of the Delphi study conducted for this research. In Round 1, the panel was asked to analyze the current state of AM technology and CE UTCs. In Round 2, these results were clarified and expanded. In Round 3, the conclusions of the committee were established and in Round 4, these conclusions were presented to the committee for final thoughts and opinions. The results of this study indicate the opinions of the committee members on the various topics discussed. In Chapter V of this document, these results will be used to answer the investigative questions posed in this thesis and will be discussed as they relate to the thesis research objective.

V. Conclusions and Recommendations

The objective of this chapter is to present the conclusions that were drawn from this research concerning AM applications for deployed Air Force CE operations and the recommendations for future work in this area. This Chapter will first review the investigative questions that guided the research and answers to these questions based upon the results presented in Chapter IV will be provided. These answers will then be applied to the research objective of this thesis. Next, the beneficial application of the Delphi technique in this research will be discussed. Finally, this chapter will discuss potential follow-on research and recommendations for action drawn from the results of this research.

Investigative Questions Answered

To meet the objective of this research, three investigative questions were analyzed. The results of the Delphi study conducted for this research were applied to these questions to reach a final conclusion on the overall research objective of this thesis. Each of these questions and the relevant results from the Delphi study are presented below.

1) *What categories of AM machine are currently well suited for utilization in CE equipment UTCs?*

Several question presented throughout the Delphi study were designed to address this question. In Round 3 of the study, the respondents did not agree or disagree with the categories of machine presented. Therefore, there appears to be some uncertainty about this topic. Further research is recommended to determine which category of machine would be well suited for this application as the panel was unable to reach a final opinion on this topic.

2) *What attributes make an AM machine well suited for use in a CE equipment UTC?*

In Rounds 1 and 2 of this study, the desired qualities for an AM machine used for CE UTCs were determined and prioritized. In Round 3, panelists were asked if they agreed with the ranking established in the previous rounds. Responses showed that panelists agreed that the following qualities are most important: usability, reliability, adaptability, and flexibility. These are the qualities this panel of experts agreed make an AM machine well suited for use in CE UTCs.

3) *Has the AM industry currently reached a point at which the selected categories of AM machines embody these beneficial attributes?*

Throughout this Delphi study, various timeframes were looked at to answer this question. In Round 1, almost 40% of respondents agreed that current technologies would be beneficial in a CE UTC. An additional 25% of respondents believed that technology would be adequate in the next five years. Ultimately, in Round 3, participants agreed that technology has currently advanced enough for a pilot or case study and that within five years, full scale deployment of an AM machine would be beneficial for CE UTCs.

Conclusions of Research

These three investigative questions provide context and background to meet the objective of this research. The research objective for this thesis is to determine if additive manufacturing machines would be beneficial if included in an Air Force CE equipment UTC and to predict the appropriate timeframe for this inclusion. Based on the answers to these three investigative questions, the members pooled in this Delphi study believe that:

1) Including an AM machine in a new UTC would be beneficial in meeting deployed CE requirements.
2) AM technology has currently reached a point at which a pilot study would be beneficial to validate the benefits of including an AM machine in a CE equipment UTC.
3) Within the next five years, AM technology will have progressed far enough that a full-scale deployment of AM machines in CE UTCs will be beneficial.

These statements, drawn from experts who participated in the Delphi study conducted for this research, satisfy the research objective of this thesis.

Delphi Application

The use of the Delphi technique in this study proved to be beneficial for this research. The Delphi method was selected for its power to predict future possibilities, but was also useful in bringing together diverse expertise and geographically separated panel members. The goal of this research was to understand future possibilities for AM applications in Air Force CE applications. This Delphi study was particularly useful for this task as The Delphi technique is a powerful tool for forecasting future possibilities (Miller, 2006:1). Additionally, this research drew upon the experiences of two disparate groups of experts. Once again, the Delphi study is particularly adept at bringing dissimilar groups together and combining and analyzing the panel discussions (Hsu &

Sandford, 2007:5). Further, these experts, although geographically separated were brought together by the Delphi study and were able to generate and share ideas and predictions. The nature of the Delphi study allowed each participant to learn from and build on the ideas presented by other panel members, and thus to increase the overall productivity of the study (Keeney, Hasson, & McKenna, 2006:206). For these reasons, the Delphi study was well suited for use in this application and a valuable tool in meeting the objectives of this research.

Additionally, several members of the panel commented in open-responses about the application of the Delphi study in this research. Three participants mentioned that the study was beneficial in exploring new technologies. Further, positive feedback was provided about the overall study in six separate responses in Rounds 3 and 4. Four participants commented about the usefulness of the Delphi study in justifying the proposed pilot study. This additional feedback provided by the panel members further substantiates the application of the Delphi technique in this research.

Significance of Research

This research is the first of its type looking at AM technology for Air Force CE contingency applications. As such, it provides a baseline for further research. This research can be used by decision makers to understand the importance of AM technology, to consider the possible applications of a deployed AM machine, and as a basis for a pilot study for deployed AM applications.

Chapter II of this thesis contains a literature review of current AM technologies. This review included an assessment of current military applications of AM machines.

This review provides context and up-to-date information about the benefits of AM technology, which are important for decision makers. This research is significant as it has shown that AM technology is an important, disruptive technology that decision makers should understand the importance of and not overlook for CE UTC applications.

Additionally, this research provides decision makers with expert opinions on the benefits of deploying an AM machine in a CE UTC. It has been shown that using an AM machine in contingency operations would be beneficial for Air Force CEs. Such application would provide a quick and powerful platform for creating necessary parts on site and on demand. However, the raw materials used in additive manufacturing should be carefully considered and topics such as material sourcing and safety must be addressed prior to AM machine implementation. These benefits and possible drawbacks are further detailed in Chapter IV of this thesis. This research is noteworthy as it is the initial work in identifying these beneficial applications for Air Force CE decision makers.

Finally, this research has identified that experts in CE UTC management and the AM industry agree that a pilot study would be beneficial for the AF CE community. A pilot study would provide decision makers with further information to determine how AM technology can beneficially meet deployed requirements. This research is significant in that it identifies the need for a pilot study and provides basic direction for what the study should examine.

This research is significant in providing decision makers with information to understand the importance of AM technology, to consider the possible CE applications of a deployed AM machine, and as a basis for a pilot study for contingency AM applications. Because AM technology is still untested for CE deployed uses, this research is preliminary in nature. However, it is significant as a first step in understanding future possibilities for this new AM application.

Limitations of Research

Due to the nature of this research, the applicability of these findings is limited. Specifically, this research is limited in application to the Air Force CE career field. The research focused on the applicability of AM machines only for CE uses and applications. Therefore, the application should be limited to this single career field within the AF and should not be broadened to the AF as a whole, or to deployed applications in general.

Additionally, the conclusions of this research are limited, as the results are opinion based and are not indicative of the participants' respective populations. The findings from this thesis represent the opinions of the panel formed for this purpose. Although this is useful information, it is not designed to be a statistical representation of the opinions of a general population. Therefore, the generalizibility of findings from this study is limited.

Recommendations for Action and Future Research

Several actionable items have arisen as a result of this research. Each of these items warrants future analysis and will further expand upon the results of this thesis. Future action should be taken to institute a pilot study as described in Chapter IV of this thesis. Additionally, it would be beneficial to further assess which items in CE UTCs are good candidates for contingency AM production, and which category of AM machine would be best suited to produce these parts through further research. Each of these topics is discussed further in this section.

Pilot Study.

Of foremost importance, this research recommends that a pilot study be created to further analyze the feasibility and benefits of deploying AM machines to meet CE contingency requirements. The experts who contributed to the Delphi study that was conducted as a part of this research agree that a pilot study would be beneficial in further validating the assumed benefits of deploying an AM machine to meet CE requirements. Additionally, panel members agree that the study should be designed to test the actual ability of an AM machine to meet CE needs in a deployed environment. This study should also test the "-ilities" of both an AM machine and the parts it produces in a deployed environment. This pilot study should build upon the findings of this research and the opinions of the experts who contributed to the Delphi study herein to further understand the future possibilities and benefits of a deployed CE AM machine. To meet these requirements, a small-scale pilot study should be created, which would consist of three phases: procurement, training, and integration. These three phases are shown in Figure 3 along with a notional timeline for their implementation.

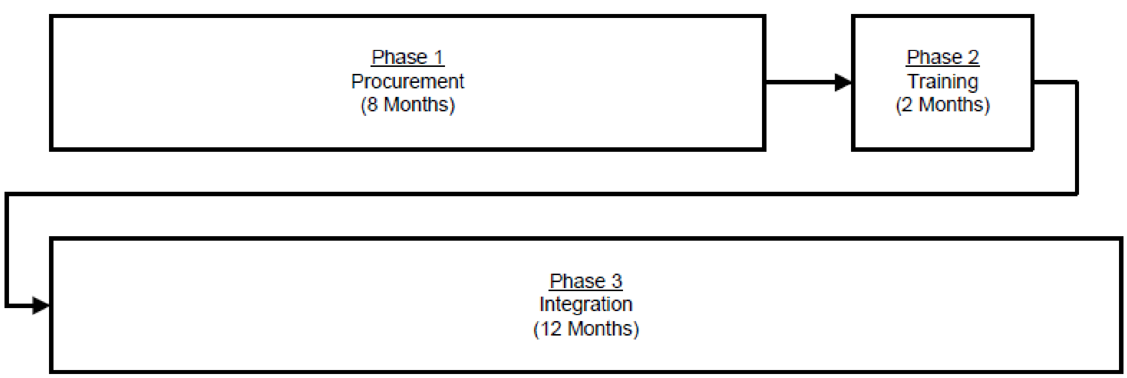


Figure 3. Pilot Study Phases and Notional Timeline

In phase one of this pilot study, procurement, further research should be conducted to determine which AM machine will best provide the benefits described in Chapter IV of this research: namely, the selected machine should enable production of necessary tools and parts on site, and on demand, be able to produce parts that will reduce inventory requirements at its deployed location, and free the location from some aspects of the traditional supply chain. Once the determination is made for an AM machine that will best provide these benefits, sourcing options for the machine should be considered. Additionally, in this stage a determination for where the initial AM machines will be deployed should be made. This pilot study should include the purchase and deployment of three AM machines to large, contingency bases. A training plan tailored to the selected AM machine should also be created for use in phase two; two or three individuals from the CE squadron at each selected base should be identified as AM machine trainers and sent to learn about the selected printer's capabilities, operations, and maintenance during phase one. These trainers will be employed in teaching other CE personnel about the selected printer in phase two. Finally, the actual procurement should occur as a single purchase to decrease initial capital costs.

Once the 3D printers are purchased and delivered, the selected bases can begin training, phase two. The personnel selected as trainers will begin instructing base CE personnel according to the training plan created in phase one. This will begin to build the pool of qualified civil engineer AM machine operators. The trainers will also be responsible for the overall operation and maintenance of the AM machine once their base has taken delivery of it.

In phase three, integration, trained operators will begin utilizing the AM machine and actively pursuing opportunities for its use and integration into their existing CE operations at the contingency base. This integration will determine if the benefits predicted by this Delphi study will be achieved in a real-world contingency environment. The operators should also begin producing parts to evaluate the "-ilities" of both the printed parts and of the selected machine during contingency operations. This phase should last for approximately one year before the pilot study is concluded and the results are used to validate or dispute the findings of this thesis research.

Other Research.

In addition to the implementation of a pilot study as a follow-on to this thesis, further research should be conducted to determine which parts within current UTCs are good candidates for production by a deployed AM machine. Future research should determine which parts and tools in UTCs could be easily produced and by which category of machine. Future research should also focus on the supply chain implications that would arise by producing these parts and tools by AM versus the traditional UTC delivery.

Finally, this proposed research of producible parts should be combined with the research conducted in this thesis to determine the most beneficial category of AM machine to deploy for CE applications. This recommendation will depend largely on which parts and tools are determined to be good candidates for AM production within existing UTCs. Proper identification can then be combined with this research to determine the most beneficial category of AM machine to deploy in a CE UTC.

Conclusion

This research has determined that 1) including an AM machine in a new UTC would be beneficial in meeting deployed CE requirements. 2) AM technology has currently reached a point at which a pilot study would be beneficial to validate the benefits of including an AM machine in a CE equipment UTC. 3) Within the next five years, AM technology will have progressed far enough that a full-scale deployment of AM machines in CE UTCs is expected to be beneficial. This novel application of AM technology is currently untested but the panel of experts assembled for this research believe that including an AM machine in a CE UTC would be beneficial and the time to begin planning for this integration is now.

Appendix A – Delphi Round 1 Questionnaire

3D Printing Applications in CE UTC Kits
A Delphi Study
Primary Researcher: Captain Seth Poulsen
United States Air Force, Air Force Institute of Technology

Questions for Round One of the Delphi Study

structions: Please answer **any or all** of the following questions. If the question is outside of you area of :pertise, do not feel that you have to guess, blank answers are fine. "Open Response" blocks have been ovided for several questions if you would like to explain or elaborate on your answers. Additional information out 3D printers and UTCs is provided as an attachment to this document if you would like additional context.

1) What qualities of a 3D printer would make it well suited for use in a CE UTC or in a deployed or field operating environment? Please circle up to **FOUR:**

   Quality Safety Usability Resilience

   Reliability Flexibility Adaptability Interoperability

   Other: ______________________________

   Open Response: ______________________________

2) In our ever changing society, many technologies become obsolete quickly or are surpassed by better products. With this in mind, which categories of 3D printer show potential to endure many years into the future? See attached *ASTM F-42 Classification of Additive Manufacturing Processes* for more information on each category if desired. Please circle up to **THREE:**

   Powder Bed Fusion Binder Jetting Directed Energy Deposition

   Vat Photopolymerization Material Extrusion Material Jetting

   Open Response: ______________________________

3) Do you think 3D printing technology has currently reached a point where including a 3D printer in a UTC would be beneficial? Circle **ONE:**

   Yes No

4) If you do NOT think including a 3D printer in a UTC would be beneficial yet, when do you think technology will progress far enough that inclusion would be beneficial? Circle only **ONE:**

1-5 years   5-10 years   10-15 years   15+ years

Open Response: ____

____

____

____

5) Which types of CE UTCs could be most benefited by inclusion of a 3D Printer? Circle **ALL** that apply:

Light Construction   Heavy Construction   Construction Admin

Explosive Ordinance Disposal   Surveying   Other: ______________

Open Response: ____

____

____

____

6) What are some potential benefits of including a 3D printer in a CE UTC? Open Response:

____

____

____

____

7) What are some challenges that may arise from including a 3D printer in a CE UTC? Open Response:

____

____

____

____

8) Do you have any additional comments? Open Response:

____

____

____

Appendix B – Delphi Round 2 Questionnaire

3D Printing Applications in CE UTC Kits
A Delphi Study

Primary Researcher: Captain Seth Poulsen
United States Air Force, Air Force Institute of Technology

Questions for Round Two of the Delphi Study

Instructions: Please answer **any or all** of the following questions to the extent that you are familiar with the issues. If the question is outside of your area of expertise, do not feel that you have to guess, blank answers are fine. "Open Response" blocks have been provided for several questions if you would like to explain or elaborate on your answers.

1) After compiling the possible BENEFITS of including a 3D printer in a CE UTC, six common themes were discovered among Round 1 respondents. Of these six possible benefits, which do you believe are the most promising for the future of deployed civil engineer operations? Please rank the following from 1 (most promising) to 6 (least promising) by inserting a rank next to each option:

Rank	Option
	3D printers allow on-demand and **RAPID PRODUCTION**
	3D printers allow production of **PROTOTYPES AND MODELS** on site and in real time
	3D printers can be used to produce necessary and **SPECIALIZED TOOLS** on site
	3D printers can be used to produce **SPARE PARTS** when needed
	3D printing capabilities can enable a **REDUCTION OF INVENTORY** of parts, tools, etc
	3D printers allow independence from some aspects of a traditional **SUPPLY CHAIN**

2) After compiling the possible DRAWBACKS of including a 3D printer in a CE UTC, six common themes were discovered among Round 1 respondents. Of these six possible drawbacks, which do you believe are the most important to address before considering 3D printers for deployed CE applications? Please rank the following from 1 (most important to address) to 6 (least important to address) by typing a rank next to each option:

Rank	Option
	3D printing **RAW MATERIAL** concerns, such as sourcing and safety
	TRAINING requirements for 3D printer operators and users
	COST prohibitive nature of 3D printers and materials
	Careful consideration of 3D **PRINTER** characteristics in a deployed environment
	Availability of necessary **SOFTWARE** and a "library" of items to print
	POWER SUPPLY for 3D printers

3) 80% of Round 1 respondents believe that a 3D printer would be useful in at least one variety of UTC; however, no consensus was reached for which type would be best. Do you believe it would be better to (highlight one):

Include a 3D printer in existing UTCs?

Create a new, 3D printing specific UTC?

Consider other methods for deploying a 3D printer?

OPTIONAL: Please explain your reasoning and/or provide suggestions for an alternative method.

Please click in this box to type.

4) Multiple respondents mentioned the differences between plastic/polymer 3D printers and metal 3D printers. How beneficial do you believe inclusion of each of these types of 3D printer would be in a CE UTC? Please highlight ONE number for each:

	Not at all beneficial			Very beneficial
Plastic/Polymer:	1	2	3	4
Metal:	1	2	3	4

5) Several respondents mentioned the use of locally sourced materials for 3D printing. How important do you believe it would be to choose a 3D printer for CE UTC application that can use locally sourced materials? Please highlight ONE number:

Not at all important			Very important
1	2	3	4

6) A 3D scanner is a device that creates a digital shape file by scanning a 3D object. Several respondents suggested including a 3D scanner in addition to a 3D printer in a CE UTC. How important do you believe it would be to include a 3D scanner? Please highlight ONE number:

Not at all important			Very important
1	2	3	4

7) A pilot study or case study to test the usefulness and possible applications of a 3D printer in CE UTCs was suggested in several Round 1 responses. In your opinion, would such a study be useful for further determining possible future applications of 3D printers in CE UTCs? Please highlight ONE:

Yes / No

8) What aspects should be tested and what should be the scope of a pilot or case study if one was to be conducted? Open Response:

Please click in this box to type.

9) Do you have any additional comments? Open Response:

Please click in this box to type.

Appendix C – Delphi Round 3 Questionnaire

3D Printing Applications in CE UTC Kits
A Delphi Study

Primary Researcher: Captain Seth Poulsen
United States Air Force, Air Force Institute of Technology

Questions for Round Three of the Delphi Study

Introduction: This round is designed to "garner consensus and/or highlight differences in opinions on the topic of discussion" as previously described. I have compiled the results of the previous two rounds in an effort to highlight the main points that have arisen and been discussed. Each of these points reflects the majority of the responses from Rounds One and Two. These questions will ask you if you agree with the group on these points.

Instructions: Please answer **all** of the following questions. Each question highlights one of the main points of the study and you are asked to decide on a scale of 1 to 5 if you:

1 = AGREE with the main point
2 = SOMEWHAT AGREE with the main point
3 = NEITHER agree nor disagree with the main point
4 = SOMEWHAT DISAGREE with the main point
5 = DISAGREE with the main point

Additionally, an "Open Response" block has been provided at the end of the questionnaire if you would like to explain or elaborate on any of your answers. Thank you so much for your participation!

1) The types of 3D printer best suited for use in deployed CE operations are Powder Bed Fusion or Directed Energy Deposition printers. Two other promising options are Material Extrusion and Binder Jetting. Please circle or highlight one:

   AGREE 1 2 3 4 5 DISAGREE

2) The quality of a 3D printer most important to consider for deployed CE applications is printer Usability. Additionally, Reliability, Flexibility, and Adaptability are qualities of secondary importance. Please circle or highlight one:

   AGREE 1 2 3 4 5 DISAGREE

3) A 3D printer which prints in metal is most likely the best option for CE applications but plastic/polymer printers should not be completely ruled out. Please circle or highlight one:

   AGREE 1 2 3 4 5 DISAGREE

4) The most promising benefit of a deployed 3D printer for the CE community is the ability to create specialized tools and parts on site and on demand. Please circle or highlight one:

   AGREE 1 2 3 4 5 DISAGREE

5) The most important drawbacks to address before deploying a 3D printer for CE operations are the source, cost, and safety of the raw material for the printer. Additionally, training requirements, printer characteristics, and initial costs are secondary drawbacks which should be addressed. Please circle or highlight one:

   AGREE 1 2 3 4 5 DISAGREE

6) In order to most effectively deploy a 3D printer for CE use, a new UTC should be created or another avenue of deployment should be considered. Please circle or highlight one:

AGREE 1 2 3 4 5 DISAGREE

7) Creating a pilot study or case study for 3D printer deployment would be very beneficial and technology has progressed far enough that this initial study can be performed today. Within 5 years it is expected that this technology will have progressed enough that full scale deployment of a 3D printer will be beneficial. Please circle or highlight one:

AGREE 1 2 3 4 5 DISAGREE

The following questions are in regards to creating a pilot or test study such as the one mentioned in question 7 above and as previously discussed in Round 2 of this Delphi study.

8) This study should primarily be designed to test the ability of a 3D printer to meet real world CE requirements in a deployed environment. Please circle or highlight one:

AGREE 1 2 3 4 5 DISAGREE

9) This study should also be designed to focus on the quality of the parts printed in a deployed environment and their suitability for CE applications. Please circle or highlight one:

AGREE 1 2 3 4 5 DISAGREE

10) This study should also consider the "ilities" of a 3D printer when used in a deployed environment. These "ilities" include usability, adaptability, reliability, maintainability, etc. Please circle or highlight one:

AGREE 1 2 3 4 5 DISAGREE

OPTIONAL - Open Response: Please use this space to explain or elaborate on any of your answers or provide any additional comments you may have.

Appendix D – Delphi Round 4 Questionnaire

INSTRUCTIONS: Please review the results in the attached document. After reviewing the information, please consider the following questions and provide any final comments or responses you would like to contribute or which have not been captured in the previous rounds of this study. A simple reply email will suffice for your response.

Do you feel these statements are an accurate reflection of the committee's opinions?

Do you feel these statements include your inputs and opinions?

Do you have any final comments?

Appendix E – IRB Exemption Letter

DEPARTMENT OF THE AIR FORCE
AIR FORCE INSTITUTE OF TECHNOLOGY
WRIGHT-PATTERSON AIR FORCE BASE OHIO

31 July 2014

MEMORANDUM FOR DR. VANCE VALENCIA

FROM: Jeffrey A. Ogden, Ph.D.
AFIT IRB Research Reviewer
2950 Hobson Way
Wright-Patterson AFB, OH 45433-7765

SUBJECT: Approval for exemption request from human experimentation requirements (32 CFR 219, DoDD 3216.2 and AFI 40-402) for 3D Printing Delphi Study

1. Your request was based on the Code of Federal Regulations, title 32, part 219, section 101, paragraph (b) (2) Research activities that involve the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures, or observation of public behavior unless: (i) Information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and (ii) Any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.

2. Your study qualifies for this exemption because you are not collecting sensitive data, which could reasonably damage the subjects' financial standing, employability, or reputation. Further, you are not collecting and reporting any demographic data which could realistically be expected to map a given response to a specific subject.

3. This determination pertains only to the Federal, Department of Defense, and Air Force regulations that govern the use of human subjects in research. Further, if a subject's future response reasonably places them at risk of criminal or civil liability or is damaging to their financial standing, employability, or reputation, you are required to file an adverse event report with this office immediately.

7/31/2014

X Jeffrey A. Ogden

Jeffrey A. Ogden, Ph.D.
IRB Exempt Determination Official

Appendix F – Open-Response Question Submissions

Round 1 Open-Response

Not practical for a fire department

You should consider adding 3D scanning capability to the UTC also. Can support reverse engineering of parts or scanning of structure

FDM machines have been attempted for use in space with limited success and application. For a CE UTC, however, the applications would be more extensive and immediate. It would be good to do a trial run and gain some experience using a simple FDM setup to determine if it can solve some field problems. Later, a metal system could be used for wider applications & the more robust tools included in a CE UTC.

The existing benefits are significant and near-term realizable improvement will be dramatic – the key will be thoughtful integration and appropriate exploitation.

Potential is limited to environment and stage of build up

More potential during sustainment than bare base arrival

From my limited research, seems to be a great technology with great potential...

I can envision it being used at structures shops performing R&D or even those that have specialized missions, i.e. those that support missile/launch facilities etc.. where on occasion they're tasked to create a special tool or part not found on a commercial shelf.

Other than that, I'm not convinced the technology is advanced enough to field as a contingency/deployable asset thus far

I honestly feel we do not have a need for this tool at this point.

Maybe if it could print or cast heavy metals it would be of use

Printer would require polymer and metal printing

Main application would be for use with build of shaped charges and charge containers

Secondary would be sustainment/repair of tools

Benefits for application for training, i.e. printing of UXO training aids

Round 2 Open-Response

Again, I don't believe this is practical for a UTC or deployed environment.

I don't feel the cost of the unit or printing materials makes purchasing and maintaining a unit like this very worthwhile.

Deploying and going to war takes us back to the basics

This type of technology would not be used or not utilized

Scanning is external only, need CAT scanning ability to capture internal structure

Should be included in a UTC, 3D printer is a tool like a hammer or screw now

Recommend a UTC specific to 3D printing

Cut cost and save materials by preventing a 3D printer being postured in (for example) each 4F9ET UTC and allow the option to be called up when needed.

Composition of a UTC could be reconstituted and reconfigured if a 3DPrinter were included

Tools that are used infrequently could be deleted and replace by an electronic file

Could be used to add fixtures or features to existing tools, reducing the array of tools that need to be included in the UTC or expanding the use of various tools.

Review the recent Marine Expeditionary Logistics (ExLog) game involving 3D Systems printers and Geomagic software. Also, review recent Rapid Equipment Force mobile fab lab operations in theater.

As and HVAC technician, I see benefits in printing fittings and generic tools
Is it economically smarter to print new vs buy new?
Investigate which UTCs would have a need for the printer
One probably needs to bundle the "3D printer" with personnel capabilities and part/software capabilities in application specific scenarios (e.g. in existing UTCs); so there would be different flavors of "3D printers" for different scenarios
To make a hammer using metal 3D printing might seem like a good idea but once you take all the above things into consideration that might not be the case
We should only apply 3D printing where it makes sense.
I saw on the news recently that NASA deployed a 3D printer to the international Space Station…Think it's a great asset for an operation of that kind but still not convinced we have the need to deploy a 3D system(s) to any of the typical locations we deploy to (which normally include reach back or local "Host nation" supply capabilities)… I will however remain optimistic and keep an open mind.

Round 3 Open-Response

Per #3, personally I think if you had to go right now and use 3D printing, I would consider starting with a production grade polymer printer and look at printing fixtures, tooling, and models. I do think there is a definite role for metal printers, but there is a very near-term opportunity for polymer systems.
Per #2, reliability is right up with usability. Otherwise if the 3D printer breaks down enough times, it will get tucked away in the corner and never get used.
My own bias is that powder-based methods are inherently expensive and subject to internal flaws that are not visible as-produced. I see merit in free-form welding integrated with local machining. (Full disclosure, I am working to try and develop this approach). Powders are messy, difficult to handle, require cleaning/classification to be recycled, and often require post processing (such as HIPping).
Polymers may be useful for drill guides, fixturing, brackets, etc. This should not be overlooked.
In general, the need for simplicity and robustness are key.
7) With limited knowledge combined with no experience with 3D printing does not lead me to a solid conclusion at this point…
Some of these questions are two part questions and can't be answered with one response. I am still of the belief that there is no valid requirement for a 3D printer in the deployed environment. But after reading these questions and not being able to relate to the topic I too feel I am not the right person to be asking. 3D printing could be feasible but from my experience it is not.
I believe the group consensus is on target for the most part. The areas where I have some difference in opinion are in regards to the importance of binder jetting abilities and training requirements. They both were identified as secondary points and I am able to see value of the group results above my personal thoughts. All and all, it looks to me to be very promising.
Perhaps a pilot study should start with a survey of common problems or issues that use of the UTC confronts in everyday use, and then compose creative ways in which a 3DPrinter could solve or mitigate those problems. This would help define the requirements of the printer implemented in the UTC. Then application of the printer to address some of those scenarios could be used as test cases as part of the evaluation. In other words,

success of 3DPrinting as a part of a UTC might depend critically on careful deliberation about the typical uses for a printer in the field, and then specifying the right printer and procedures to meet those requirements.

Nice job on the study!

Again, I don't think this would be applicable for Fire Department use, but possibly in other CE areas. The parts created or printed would be very specific and beneficial, but the benefits and printing would have to outweigh the cost of shipping, storage, maintenance, training, programming, fuel, electricity, and most importantly, the cost, transportation, and storage of the bulky raw materials that are used in the printing process. With the drawdown of the conflicts in this area and the availability of building materials everywhere, I don't see this as practical. In my 16 ½ years in the Air Force and through 5 deployments, I have never heard any CE AFSC say "I wish I had a 3D printer."

Concerning pilot or test study, it is vital that collaboration occur amongst the CE AFSCs to identify/assess the total needs and mobilization requirements for the platform

In the mindset of efficiencies, I can't imagine that CE operations or emergencies services individually would have production requirements that would warrant that either would require an independent system.

One system should support all CE at one deployed location

Round 4 Open-Response

This is an interesting concept and I look forward to the possibilities that the study/ies bring to our warfighters.

I don't think this would be applicable for Fire Department use, but possibly in other CE areas. The parts created or printed would be very specific and beneficial, but the benefits and printing would have to outweigh the cost of shipping, storage, maintenance, training, programming, fuel, electricity, and most importantly, the cost, transportation, and storage of the bulky raw materials that are used in the printing process. With the drawdown of the conflicts in this area and the availability of building materials everywhere, I don't see this as practical. In my 16 ½ years in the Air Force and through 5 deployments, I have never heard any CE AFSC say "I wish I had a 3D printer."

With that said, I am only referring to this not working in a UTC. A 3D printer could have its uses at a more permanent/enduring type base like Al Udeid that has the money, infrastructure, storage, software updates, and raw material supply train to sustain an item like this.

The results don't necessarily surprise me - it seems most participants favor the technology (with some reservations).

Thanks and can't wait to see the full dissertation in final form. Much respect!

Great Job in exploring new technologies that, one day, could help CE craftsman perform their mission with a lighter more agile footprint... Thx for the opportunity to provide feedback!

"Usability" covers a different scope depending on each person's perspective. Narrowly defined, I would add, repeatability to the additional list.

More generally, I think the message is that metals 3D printers are more suited than polymer printers at this time (i.e. #3). I think the middle rating may be caused by debate over the best metal printing rather than metals vs polymer. Thus I agree with the result.

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Vita

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14. ABSTRACT
Additive manufacturing is a relatively new technique that is gaining popularity in many applications. This research examines the possibilities for the integration of additive manufacturing (AM) machines in United States Air Force civil engineer (CE) contingency operations. A Delphi study was conducted that combined the knowledge and experience of experts in both the AM industry and the Air Force CE community to forecast the possible benefits and drawbacks of this novel AM application. The results of this Delphi study indicate that including an AM machine would be beneficial in meeting deployed Air Force CE requirements. Further, AM technology has reached a point that a pilot study would be beneficial to validate the benefits of including an AM machine in CE operations. Proposed goals of, and a design for this study are presented. Further, the results indicate that within the next five years, AM technology will have progressed far enough that a full-scale deployment of AM machines to meet Air Force CE contingency requirements will be beneficial.

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