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AN ANALYSIS ON RECOMMENDED UNITED STATES AIR FORCE ADDITIVE MANUFACTURING CONSTRUCTION UNIT TYPE CODE PACKAGE FOR EXPEDITIONARY DEPLOYMENT

THESIS

Caleb G. Dann, Captain, USAF

AFIT-ENV-MS-23-M-182

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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AN ANALYSIS ON RECOMMENDED UNITED STATES AIR FORCE ADDITIVE MANUFACTURING CONSTRUCTION UNIT TYPE CODE PACKAGE FOR EXPEDITIONARY DEPLOYMENT

THESIS

Presented to the Faculty
Department of Systems Engineering and Management
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Air University
Air Education and Training Command
In Partial Fulfillment of the Requirements for the
Degree of Master of Science in Engineering Management

Caleb G. Dann, BS
Captain, USAF

March 2023

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Caleb G. Dann, BS
Captain, USAF

Committee Membership:

Maj Brigham Moore, PhD, P.E.
Chair

Mr. Tay Johannes, PhD
Member

Lt Col Benjamin Knost, PhD
Member

Abstract

Additive Manufacturing Construction (AMC) is an emerging technology in the construction industry which utilizes 3-D printing to reduce costs, labor requirements and deviations in quality. This technology has the ability to rapidly produce repeatable construction projects while tailoring each to specific requirements through the use of 3-D designs. One of the primary objectives of the 2018 National Defense Strategy (NDS) is to continue meeting mission demands with a greater focus on the efficient use of resources. AMC has the ability to satisfy the requirements of this objective. The United States Air Force has begun initial print trials but have not yet fully operationalized this technology.

This study implements several decision-making methodologies which provide leaders with a framework for implementing this technology in terms of personnel training, team composition, and equipment selection. The outcome of this work is the identification of an optimized team composition capable of performing AMC based on their current skills and potential future skills along with a methodology to select the equipment that best fits the expeditionary construction needs of the Air Force.

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AN ANALYSIS ON RECOMMENDED UNITED STATES AIR FORCE ADDITIVE MANUFACTURING CONSTRUCTION UNIT TYPE CODE PACKAGE FOR EXPEDITIONARY DEPLOYMENT

I. Introduction

Background and Motivation

Currently the United States Air Force (USAF) employs conventional construction to perform construction projects in a deployed environment. Conventional construction requires a significant amount of time and resources before structures can be erected. There are pre-construction costs, site prep, form preparation and foundation work that must be completed before a hardened structure can be erected. Each of these steps incur the consumption of both time and resources which leads to increased construction costs. (Meisel et al. 2022) These costs are both necessary and unavoidable through conventional construction thus alternative construction options should be explored with the goal of conventional construction product delivery at reduced resource costs.

The 2018 National Defense Strategy (NDS) discusses how our strategy must adapt as our primary focus changes from smaller rogue organizations to large near peer adversaries. The goal being to remain the preeminent military power in the world, ensure the balances of power remain in our favor, and advance an international order that is most conducive to our security and prosperity (Department of Defense 2018). To accomplish this goal and change in strategy, the Department of Defense (DOD) has established 11 main objectives to focus on moving forward. The objective that motivates this thesis is, continuously delivering performance with affordability and speed as we change Departmental mindset, culture, and management systems (Department of Defense 2018).

This objective motivates this problem because of the need to explore alternative construction methods capable of continuing to accomplishing the goals of construction at a reduced time and overall cost.

Conventional construction has allowed society and our military to get to the point it is today, but that doesn't mean it is the best method for moving into the future. That being said, conventional construction requires a significant amount of time, manpower and materials to successfully complete any given project. A study found that in general, human resources costs between 30 and 50% of total project cost. Those costs include both management and labor costs with the majority being attributed to labor (Dabirian, Khanzadi, and Moussazadeh 2016). These human resources costs add up quickly when considering the number of projects the military executes in any given year.

Today in deployed environments AF construction is either completed through contracting projects to local construction firms or completed by the military members stationed at the base. When the military members are performing the construction specific construction Air Force Specialty Code (AFSC) personnel are utilized based on the Unit Type Code Packages (UTC) available at that installation. An AFSC is a specific coding given to AF personnel based on the type of job and specific skillsets that they have. A UTC is a basic building block used in planning and deployments capable of completing a specified mission. One of the primary Civil Engineer UTCs is a 4FPET team which is a team of AFSCs with the mission statement of maintaining and operating an air base. The standard Civil Engineer enlisted AFSCs utilized in construction projects are included in Table 1. These specific skill compositions are leveraged to meet all skill requirements for performing construction and meeting the mission statement a specific UTC enables.

Table 1: Civil Engineer Construction AFSC List

AFSC	AFS Category
3E0X1	Electrician
3E0X2	Power Production
3E1X1	Heating, Ventilation, Air Condition and Refrigeration
3E2X1	Pavements/Equipment
3E3X1	Structures
3E4X1	Utilities
3E5X1	Engineering Assistant
3E6X1	Operations Management

Based on the main objective highlighted in the NDS we now have to continue to provide these construction capabilities at a reduced cost and in a more expedited manner. One alternative method of construction that is capable of being executed faster and with reduced resource costs is Additive Manufacturing Construction (AMC). Once proficient, a team performing AMC has the ability to provide successfully completed projects with decreased manpower, materials, time and increased geometric freedom. The reduction in resources, increase in freedom and the autonomous nature of this construction method allow for new geometries and materials to be printed in the unsafe or challenging environments expected in a deployed setting (Meisel et al. 2022).

The benefits of this emerging construction technology can be seen in any of the recent 3-D printed construction projects happening across the world. One particularly good example can be seen in the recent barracks structure built by the Texas National Guard. The Texas National Guard just unveiled the largest 3-D printed structure in North

America which can house up to 72 trainees at the Camp Swift Training Center. This project was contracted to company ICON, a Texas-based construction technologies company, and was able to be completed in less time and less money than it would have if constructed conventionally (Texas Military Department 2021). Examples of this AMC are becoming more and more prominent as this rapidly growing technology becomes a viable established form of construction.

Additionally, the speed and cost benefits provided through 3-D printed construction make it possible for great humanitarian application. In 2019, ICON set forth with the goal of developing economically affordable homes for financially challenged families. 50 families who were previously living in unsafe, temporary makeshift shelters were selected to receive housing. Despite several environmental challenges such as heavy rainfall and localized flooding, ICON was able to print these fifty 500ft^2 homes each with a 24-hr print time (ICON Team 2019). Local Non-profit organizations finished the homes and made them livable for each family. This application demonstrates the efficacy of 3-D printed construction in humanitarian application. These examples establish the desire to integrate current Civil Engineer capabilities with alternative modern technological construction processes capable of delivering conventional construction performance with reduced duration and resource expenditure. The following section will introduce the research scope and intent related to how AMC may be implemented into AF Civil Engineer expeditionary environments.

Research Scope and Intent

What this research aims to do is develop a recommended equipment and personnel UTC that can be deployed downrange to perform AMC. The research will be tailored specifically to AFSCs but the same methods used to build these packages could be used to develop similar capabilities for other components of the Department of Defense (DoD) and civilian sector as a whole. The primary research question this research aims to answer is, what are the equipment and personnel requirements to support a deployable additive manufacturing UTC? In order to answer this research question, several supporting questions will be explored to fully understand each of these requirements.

The first question to be explored is, how do we determine the personnel requirements to support an additive manufacturing project? The goal of this question is to understand what personnel requirements will be required to perform AMC. This will require an analysis on the minimum number of personnel based on independent parallel tasks evaluated through a Work Breakdown Structure (WBS) of a single AMC job. It will also require the identification of training requirements based on the printer manufacturer recommendations and the above mentioned WBS. Finally, it will require gap analysis of AFSC existing training and skills compared to the training and skills required to perform AMC.

The second question to be explored is, how do we determine the right composition of personnel to support an additive manufacturing project? The goal of this question is to determine which set of personnel should be on the AMC construction team. This will require building an optimization model capable of assigning AFSCs to the team based on minimizing cost while meeting all skill requirements. Minimum cost will be established as a function of personnel AFSCs with finite skills capable of meeting all WBS requirements. Additionally, the Multiple Capable Airmen (MCA) concept will be explored as a way to develop a cost-based parameter for personnel selection to be used in the model. In this research, MCA will be explored as a way for one AFSC to learn the skills of another AFSC making them multiple capable. Finally, a comparison analysis of a conventional 4FPET team vs a new standalone personnel UTC will be conducted to understand if there is a benefit to establishing a new specific AMC UTC.

The final question to be explored is, how do we determine the right AMC printer to support an additive manufacturing construction project? The goal of this question is to determine what printer best meets the needs of the AF. This question will be explored through determining the printer selection criteria. These criteria will be the decision-making criteria or the printer qualities which are most important for expeditionary construction. Additionally, a market analysis on the primary AMC printer manufactures will be performed to determine the set of printers to be analyzed in this research. Next, with the criteria determined a form of rank-ordering of criteria will be established through conducting an expert elicitation on the set of criteria. Finally, utility scores based on utility curves for each printer's ability to satisfy the given printer selection criteria will be developed and used in the selection model. With each of these supporting questions determined the primary research question and scope of this research are formulated and can be answered.

Expected Results and Contributions

This research will result in several different contributions to the Civil Engineer career field and to topics relating specifically to AMC implementation. Determining the personnel requirements for AMC will result in two distinct contributions. The first being that by performing a training similarity and cost analysis, the first preliminary numbers for implementing MCA in the CE career field will be produced. The second will be an optimization model that provides a way to quickly tailor personnel team members based on end user requirements and the project WBS. Finally, leveraging existing decision-making methodologies to determine the equipment requirements will yield a robust and repeatable process to evaluate equipment selection based on end user decision making criteria. Specifics on each of these expected results will be further explored throughout the remainder of this document.

Thesis Overview

This thesis is the culmination of multiple stages of research oriented toward answering the guiding supporting questions. The research begins with a literature review that delves into Current State of Existing 3-D Printing Construction, Personnel Requirements, Equipment Requirements and Expeditionary vs Garrison Construction. This research examines relevant literature and the current state of the aforementioned topics in effort to use them to recommend a personnel and equipment UTC package to perform AMC for Air Force expeditionary implementation.

Following this introductory chapter, Chapter II introduces the current literature on training requirements, skills required, Multi-Capable Airmen, UTC development methodology, printers and their selection criteria. This study is conducted in three separate but connected phases. Due to this, Chapters III through V will focus on the methods, procedures and tools used to gather data and interpret the results for developing viable options for an AMC UTC. Figure 1 helps describe these phases and serves as an outline for these chapters.

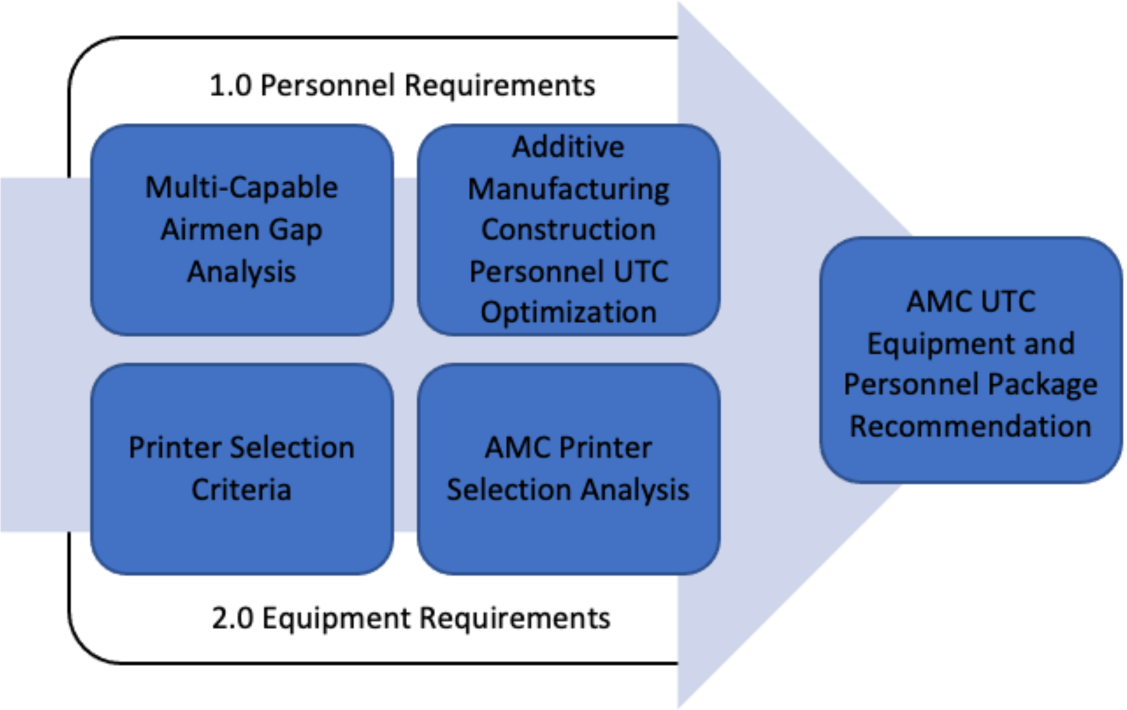


Figure 1: Major Phases of Research that Contribute to AMC UTC Recommendations

The major pieces of this report include a MCA AFSC Training Gap Analysis, a Minimum Team Model Selection, and Printer Selection. The AFSC Training Gap Analysis seeks to determine two primary features. First, what gaps in AMC skillsets are present within the current AFSC core training construct. Second, it seeks to understand how the skills of CE AFSCs overlap to establish potential costs for the multiple capable airmen concept used in the minimum team model. The Minimum Team Model uses an optimization problem to find the minimum number of personnel required to execute AMC while ensuring all tasks can be completed for the least cost. Multiple iterations of this model are performed by use of several different team compositions. Possible team compositions for both a stand-alone UTC and existing 4FPET team UTC will be explored as potential options. The Printer Selection Model is a combination of the Analytical Hierarchy Process (AHP) and Multi-Attribute Utility Theory (MAUT) to assess and weigh the selection criteria found during the literature review. Finally, Chapter VI concludes the research and provides the implications, limitations and overall recommendations for follow-on research.

II. Literature Review

Chapter Overview

This chapter summarizes the literature review conducted for this research, which provides vital information on several topics. This literature review will be composed of two primary components. The first will delve into existing research into 3-D printed construction. The second will delve into specific features of 3-D printed construction that are relevant to where research is going to be applied in this thesis document. Specifically, those features are, first, Civil Engineering (CE) AFSC Core training skills will be examined to determine what fundamental gaps in existing skills and AMC required skills exist. Second, a thorough examination of UTC creation methodology will be had as the basis for recommending the AMC UTC. Third, the differences between Gantry style and Robotic Arm style 3-D printers will be explored and those findings used in the printer selection. Fourth, an analysis on the differences in needs of home station AMC and expeditionary AMC. Fifth, a printer selection criteria analysis will be performed to determine what criteria should be used in the AHP. Finally, this chapter summarizes the main points of the literature review and how they will be used throughout the remainder of the thesis.

Current State of Additive Manufacturing Construction

Existing research into AMC is relatively limited due to the topic's academic infancy. To start this literature review it was important to understand what AMC is, how it is being used currently, who is currently using it, and its pros and cons to set up the research into how this technology could be used in AF expeditionary environments.

Through initial investigations it was clear that this technology was very new and that it was seeing the most use in the Civilian Sector with many major 3-D printed construction companies emerging. Early developments of 3-D printed construction capability emerged in the 1990s. The technology at this time was limited to scale models and parts rather than large structures. In the 2000s, 3-D printed construction applications were in full swing and getting set to transform the entire industry (Head 2017). Now, AMC is has taken hold and its potential is being explored throughout both military and civilian sectors.

ICON, one of the primary AMC companies in the civilian sector has found great use in the production of small, affordable and repeatable homes for economically disadvantaged locations (ICON Team 2019). These companies are also working towards building multi-story buildings with the use of 3-D printers. Currently, these civilian companies are all striving towards producing the best product at the least cost. While perfecting the application of AMC is a focus, these major companies exploring and expanding these applications is also a primary focus. Companies on the forefront of this technology are speculating on expanding capability to space application and developing systems capable of producing fully function facilities (roofs, utilities, heating and ventilation, etc) (Head 2017).

The military is behind the civilian sector in terms of AMC use but research has begun and use cases are being developed. One of the primary explorations into how the military can use this technology was conducted through the Army Research Lab (ARL). The ARL conducted a case study on 3-D printed construction in expeditionary environments with a custom-built printer which utilized existing locally available concrete mixes. This report concluded that 3D-printed construction was faster, safer, less labor-intensive, and more structurally sound than conventional construction methods. It also concluded that the use of commercially procured, pre-mixed materials introduced additional cost, logistical burden, and adverse environmental impact as compared to traditional conventional concrete methods (Jagoda et al. 2021). More specific information on this case study can be found in the article *The Viability and Simplicity of 3D-Printed Construction: A Military Case Study*. The Texas National Guard has also begun testing the implementation of 3-D printed construction with the recent barracks unit constructed at Texas Camp Swift Training Center. The Air Force has also begun researching 3-D printed construction for use in EOD blast testing. As of 2022 AFCEC has acquired, set up and begun running trial prints for the use of explosive testing procedures (Nikon 2022). The goal of these tests is to understand the impact of explosives on these structures. In each of these cases a simple and repeatable structure is what is being tested and is a commonality in the structures being produced at this time.

The ARL case study introduced several pros and cons to this technology which were validated and expounded upon with other research conducted in this field. One article in particular that discussed the concept of print time vs real world time in relation to cost is *Development of the construction processes for reinforced additively constructed concrete*. This article takes the ARL barracks printed project and discusses it in terms of print time vs total elapsed time. It highlights the importance in discussing both print time and total elapsed time because although it may take only 14hrs to print a structure the real-world project time could be significantly more (Kreiger, Kreiger, and Case 2019). That said, because labor costs make up a significant portion of overall construction costs it highlights a significant potential for construction cost reduction using AMC. These results show the viability and effectiveness of utilizing AMC and how the AF could benefit from its implementation.

Two more research pieces that proved vital to this document were *A Delphi Study of Additive Manufacturing Applicability for United States Air Force Civil Engineer in Contingency Operations* and *In-Situ resource-based lunar and Martian habitat structures development at NASA/MSFC.* The Delphi study introduced existing criteria deemed critical to AF expeditionary engineering dominated by several "ilities" including but not limited to Usability, Reliability, Adaptability, Flexibility (Poulsen 2015). What was not in this document that I did find in the In-Situ article was the importance of using what you have locally available. Given the limited space and extreme costs associated with transporting anything to extraterrestrial environments using existing materials becomes critical. This article delves into the use of In-Situ materials to perform construction and the benefits associated with automated Martian construction versus conventional construction (Bodiford et al. 2005). This article in combination with the military case study highlight the importance in reducing costs and logistical burdens associated with transporting pre-mixed printing concrete through the use of local materials.

Each of these topics helped build the case of how this technology was currently being used and how it could be selected an implemented into the AF expeditionary construction toolkit. The remainder of this literature review will focus on topics that drive toward the goal of developing a methodology to select and implement 3-D printed construction into the AF construction toolkit. That toolkit starts with the skills currently known and the skills required to perform AMC in AF expeditionary environments.

Personnel Requirements

To understand what skills are required for performing AMC and if current AFSCs have those required skills, the manufacture skill specifications must first be understood. Once the skillset required is obtained, those skills can be compared to the documented AFSC skillsets to determine if any skill gaps exist. Through interviews with leading printer manufacturers and reviewing printer specifications, the only definitive skill gap that exists is a fundamental equipment training (Aaron Hoffman 2022). Training to use this new piece of equipment is not fundamentally different then just training and being certified to operate any other piece of heavy equipment. There is no fundamental skill gap between what is already known with general construction and what must be known to complete 3-D printed construction. A 3-D printer is just another piece of equipment that can be used to complete a construction project. As long as the project team understands general construction and receives the training on that new piece of 3-D printer equipment, there should be no skill gap preventing a successful completion of that project (Aaron Hoffman 2022).

With the skill gap identified, the second piece of this analysis is to understand the skillsets of each AFSC to identify how they overlap and what that could mean for the multiple capable Airmen concept that will be later used in the team selection model. Skillsets of each AFSC are defined by both their AFSC itself and their grade in that AFSC. Brand new airmen, 3-levels, 5-levels and 7-levels will all have a different set of skills based on their progression through upgrade training. For this research, the assumption that airmen will be in the 5/7-level range will be used. This assumption was made because and Airmen should progress enough in their career field before being considered for multiple skillsets outside their AFSC. These AFSC skillsets are laid out in each of the CE AFSC Career Field Education and Training Plans (CFETP). Each CE CFETP defines the core and diamond skills that an Airmen in the 5 and 7 level should have, at a minimum. Core tasks are mandatory tasks which the Air Force Career Field Manager (AFCFM) has identified as a minimum qualification requirement within an Air Force Specialty (AFS) or duty position. These tasks exemplify the essence of the career field. Diamond tasks are the same as core tasks with one exception--equipment shortfalls at most locations have created problems with the actual hands-on training and certification of these tasks. In instances where required equipment is not available for instruction, completion of the task's Air Force Qualification and Training Plan (AFQTP) is all that is required for upgrade and qualification training (United States Air Force 2022). With the skillsets of all involved CE AFSCs identified a comparison analysis can be conducted and used in the team minimization model discussed in the methods and results section of the thesis.

The concept of Multi-capable Airmen (MCA) is relatively new but is vital to the future of the Air Force and the United States ability to remain the preeminent military power across the globe. In an environment that includes, but is not limited to, declining resources, aggressive global competitors, and rapid technology development and diffusion, the U.S. Air Force must accelerate change to control and exploit the air domain. Airmen must be multi-capable and adaptable team builders, as well as innovative and courageous problem solvers, and demonstrate value in the diversity of thought, ingenuity, and initiative (General Charles Q. Brown 2020). MCA are defined as, "Airmen capable of accomplishing tasks outside of their core Air Force Specialty. Personnel are often trained as a cross-functional team to provide combat support and combat service support to Agile Combat Employment (ACE) force elements. They are enabled by cross-utilization training and can operate independently in an expeditionary environment to accomplish mission (Cuellar 2022). This definition and how it is implemented across the career fields allows some room for interpretation. For the purposes of this research, MCA concept will be utilized as individuals capable of performing tasks outside of their specialty code skills to perform CE functions.

In the CE career field, the MCA concept is in a nascent stage. This means that there is a fundamental gap in the research when it comes to what MCA means for AF Civil Engineers. In theory, it could mean is that one CE AFSC is capable of performing the skills of its own AFSC and of one or more other AFSC's. The need for the development of MCA in the CE career field goes back to the primary motivation of this thesis and the motivation provided in the memorandum from General Brown(General Charles Q. Brown 2020). If one AFSC was capable of performing the skills of several AFSCs team compositions could be smaller, less costly and more agile while maintaining the skills required to successfully complete construction projects. Due to the lack in guidance for MCA execution in the CE career field, for this research each CE AFSC will be able to learn the skills required by other AFSC based training costs. This concept will be further discussed in Chapter 3.

UTCs are built by "Determining the distribution, alignment, reliability, credibility, and skills required in the Civil Engineering Manpower resource to perform essential Civil Engineer functions in support of the Air Force mission" (Michelle Y. Lafferty 2017a). UTC building methodology has changed several times since their inception back in 1964 (United States Air Force 2019b). The original large UTC construct was based upon a “build the base” mentality but over time as there is less “build the base” deployments and more sustainment operations these large UTCs were deemed to be too large thus pushing towards a smaller UTC construct. The changing nature of the military “enemy” requires the U.S. to need new combinations of concepts, capabilities, people and organizations that exploit the nation’s advantages (United States Air Force 2019b).

The 4FPET team UTC was created to represent all basic CE capability regardless of mission. Table 2 shows the personnel breakdown by AFSC for the Civil Engineering 4FPET team UTC. This team is composed of 26 CE AFS personnel with one officer, 7-levels, 5-levels and 3-levels (United States Air Force 2019b). These numerical levels represent an individual’s skill level. The skill level corresponds to both rank and upgrade training requirements. Upon graduation from technical school, individuals receive the 3 (apprentice) skill level. Airmen are then normally awarded the 5 (journeyman) skill level after a specified amount of on-the-job training (OJT) and corresponding Career Development Courses (CDCs). Finally, upon promoting to Staff Sergeant, individuals begin training for the 7 (craftsman) skill level. This level of training requires more CDCs, OJT, and 7-level technical school if required (United States Air Force 2019).

Table 2: 4FPET Team Composition

AFS Category	AFSC	Quantity
Officer	32E3G	1
Electrician	3E0X1	4
Power Pro	3E0X2	2
HVAC	3E1X1	3
Pavements/Equipment	3E2X1	4
Structures	3E3X1	4
Utilities	3E4X1	5
Engineering Assistant	3E5X1	2
Operations Management	3E6X1	1
	Total	26

Table 2 displays the breakdown of the 26-person 4FPET Team. It breaks down the AFS Category and specialty code for each AFS. The specialty code for each AFS represents the particular shred out of a given AFS because there may be more than one section in a single category. For example, the 3E0 AFS has two sections, each fall under the same AFS but are responsible for different things thus they are given a different code/shred out. 3E0X1 represents an electrician whereas 3E0X2 represents Power Production (United States Air Force 2022).

The 26-person UTC is capable of a wide variety of tasks inherent in establishing and operating an airbase (Michelle Y. Lafferty 2017). However, if there is a repeatable type of work to be completed using AMC then a new personnel UTC could be developed specifically for that function. That UTC could be tailored in a way to minimize the number of personnel required by maximizing the skills of each person on that team. The AF could accomplish this by implementing a version of a MCA concept where one Airmen (AFSC) has the skills of multiple airmen (AFSCs). This methodology could maximize the number of skills that a team has while minimizing the overall number of people yet still accomplishing the goal of a UTC in being built to perform essential CE functions in support of the AF mission. This concept will be furthered discussed and explored in the remaining chapters of this thesis.

Equipment Requirements

This portion of the literature review attempts to answer the third research objective in determining the right AMC printer to support a construction project. This is accomplished by exploring what attributes make an Additive Manufacturing (AM) machine well suited for use in a CE equipment UTC or in a deployed or field operating environment (Poulsen 2015)? This question focuses on the specific attributes necessary in an AM machine for CE contingency applications. Its goal is understanding the desired qualities of an ideal AM machine and focuses on its "-ilities" such as reliability, usability, quality, maintainability, transportability and others (Poulsen 2015). 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). Several printer attributes will be discussed in the following paragraphs.

While there are many ways to use 3-D printing technologies for concrete construction, the two specific methods that are currently dominating the industry and that are the focus of this research are: (COBOD 2022)

- Gantry-type 3-D printers mainly used for larger construction and on-site
- Robotic arm 3-D printers mainly used for smaller, more complex components

Two additional types of systems, important to mention but are not the focus of this research are, Swarm Robot Systems and Cable Suspension Systems. They are similar to Gantry and Robotic arm styles but have enough differences to be classified as their own style. These two styles are in an early stage of development and thus will not be considered in this research.

At the surface level, the style of a printer impacts it's construction capability. Gantry systems make for a simple printing system design as well as a simple control system. They are typically scalable and thus are optimal for constructing larger less unique structures. Although they are scalable, a key downside to gantry-based systems is the required scale of the frame. The frame needs to be larger (often significantly larger) than the structure to be built, which can require a massive system along with costly transportation and setup processes (Labonnote et al. 2016). This can detract from the overall responsiveness of deploying a gantry-based printing system to remote environments. In addition, gantry systems typically only allow for planar movement in the *X*, *Y*, and *Z* directions, which generally limits their capability to extruding simple two-dimensional (2D) layers. However, as technology as advanced researchers have added unique capabilities to gantry systems, such as rotating nozzles, angling nozzles, and automated reinforcement placement (Labonnote et al. 2016).

Robotic arm style printers have been used extensively within AMC because of their ability to produce a wide range of geometries and ability to perform in different environments (Urhal et al. 2019). A robotic arm also minimizes the need for on-site assembly due to its compact size when folded; this eases transportation to a remote environment as well as system setup (Meisel et al. 2022). The advantage of having six axes of freedom also increases the achievable geometric complexity compared with the three axes of the cable-based and gantry-based systems (Labonnote et al. 2016). Advantageously, the multi-purpose robotic arm can hold different end-effectors to perform multiple functions that are involved in the construction process. The ability to perform tool changes along with its multi-axis design allows for use in multiple stages of construction as well as embedding items into the build. The multifunctionality of the robotic arm allows for the consolidation of hardware needed, ultimately reducing the needed equipment deployed on location (Bodiford et al. 2005). One of the most significant drawbacks of a robotic arm is its limited reach. Whereas conventional gantry systems have been demonstrated to be capable of scaling to construction-size structures, achieving similar deposition sizes with robotic arm systems is challenging (Watson et al. 2019). The main issue with robotic printing, though, is the more limited scale achievable; robots have limited reach and must be moved to print structures larger than their reach (Labonnote et al. 2016). Each time the printer is moved the process of recalibrating its location will need to be completed to ensure the printer is accurately printing. This process having to be repeated several times throughout a print adds additional time that isn't required using its gantry style counterpart systems. This is one example of how a printer attribute may affect a project.

Attributes such as style are fundamental in ensuring these new technologies usability in an environment where its personnel are constantly rotating. While criteria with the goal of accommodating users is important there are several other important criteria related to the motivation of this research. The 2018 NDS identifies reducing cost and time as important to military construction. The capability that needs be continually met is successful military construction. The criterion that enables this is captured in a printers' build size. If a printer is too small it may run the risk of continually needing to be moved and set-up which will inevitably increase overall construction duration and cost. If it is too large its transportation and set-up will become increasingly difficult and time consuming. The printer criteria that are important when considering cost and time reductions are set-up time, unit cost and use of locally available materials. The time it takes to set-up and tear-down the printer is one of the first steps that impacts the overall cost and duration of any AMC project so ensuring a printer is selected that has minimal set-up and tear-down time is vital for expeditionary construction.

Two of the primary factors that should be considered in the cost of printing are where you get materials to print and how much the initial equipment cost. A number of printers that are currently available on the market require the use of specific material for printing. Some require proprietary mixes that must be bought specifically for use in printers and some require specific mix constructs (premix) to be used in the systems dual mix and pump systems (Constructions3D 2021). These mix and pump systems require the use of this pre bagged premix and cannot utilize existing local materials without issue. The intent of this construction is expeditionary thus printers requiring this style of premix would create significant logistical burdens and increase construction costs as compared to systems that can utilize local materials. For this reason, use of local materials is an important criterion to consider when aiming to select a 3-D printer capable of performing construction at reduced costs.

Table 3: Finalized Printer Selection Criteria

Criteria Number	Criteria Name
1	Set-Up Time
2	Printer Cost
3	Use of Local Materials
4	Use Complexity
5	Transportability
6	Durability
7	Maintainability
8	Build Size

Table 3 lists the eight printer selection criteria determined to be the most vital in selecting an AMC printer for AF expeditionary construction.

Expeditionary vs Garrison 3-D Printing Construction Differences

There is a fundamental difference between construction in a deployed environment and at home station, that fundamental difference is whom is most likely to be performing the construction. That key difference is, in deployed environments airmen should expect to perform hands on construction whereas at home large construction projects can be expected to be contracted work. Based on this key difference the printer selection criteria will carry different weights under different scenarios. At home, a contractor will be responsible for completing a project that the Air Force as the customer requests. Because of this, the Air Force won't necessarily place as much weight on durability, maintainability, ease of use, transportability, use of local materials and set-up time but will care a lot more about build size, speed, total cost, accuracy and freedom of design. The customers focus will be on the project being completed fast (speed), cheap (total cost), and meeting all requirements (accurate, build size and freedom of design) and less on how it was completed. In a deployed environment military members will be responsible for the successful completion of the construction project so all of the criteria previously mentioned that mattered less now matter and those that did matter will matter less. In expeditionary environments where airmen are responsible for using and maintaining equipment said equipment should be easy to use, durable, easy to set up and tear down, transportable and readily available materials need be used to reduce logistical burdens. These fundamental differences could mean that one printer could be better suited for home station construction and another for expeditionary construction.

Summary

This chapter has reviewed the personnel requirements, equipment requirements and Expeditionary vs Garrison 3-D Printing Construction Differences for AF AMC. This information is provided as a background to the research conducted and will be further used in the remaining chapters of this thesis document. The following chapter, Chapter III, will discuss how this information was used in building the methodology utilized in this research.

III. Multi-Capable Airmen Gap Analysis

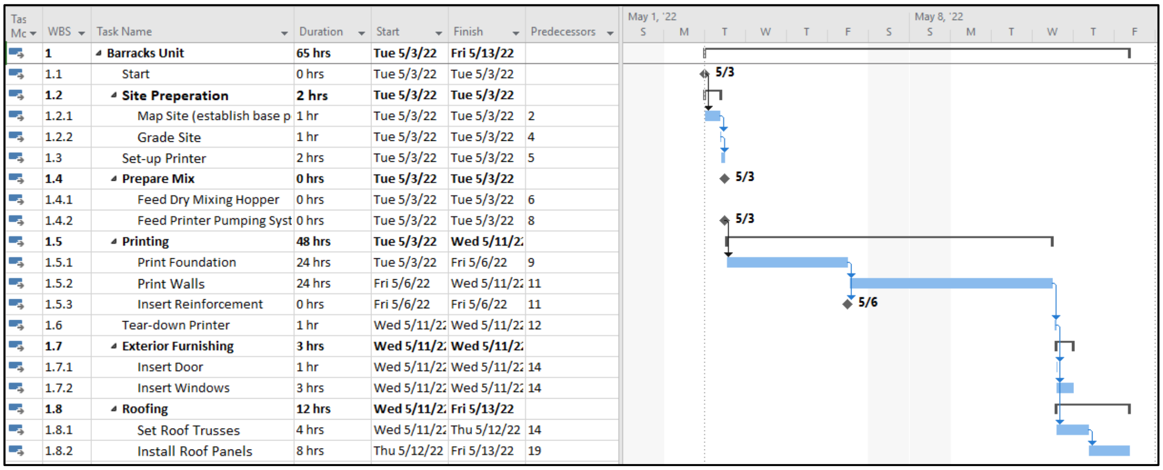
Chapter Overview

This chapter summarizes the approach taken to complete the Multiple-Capable Airmen (MCA) Gap Analysis portion of this research. This portion of the research is vital to the results because the data gathered in this section feed into Chapter IV, the AMC Team Selection Model. This gap analysis is composed of two primary components, the AMC skill requirement gap compared to existing AFSC skills and second, the skill comparison analysis between existing AFSC skillsets. The gap analysis between existing AFSC skills is itself composed of several sub components. Those sub-components are a specific project work breakdown structure (WBS) to identify specific skill requirements, enlisted initial skills training costs (dollars per day attributed to each AFSC training) and CE AFSC AFQTP lists for each trade. With these sets of information, an MCA parameter based on training and cost can be established for use in Chapter IV, developing an optimization model for an AMC Personnel Team UTC.

Work Breakdown Structure vs AFSC Skills Gap Analysis

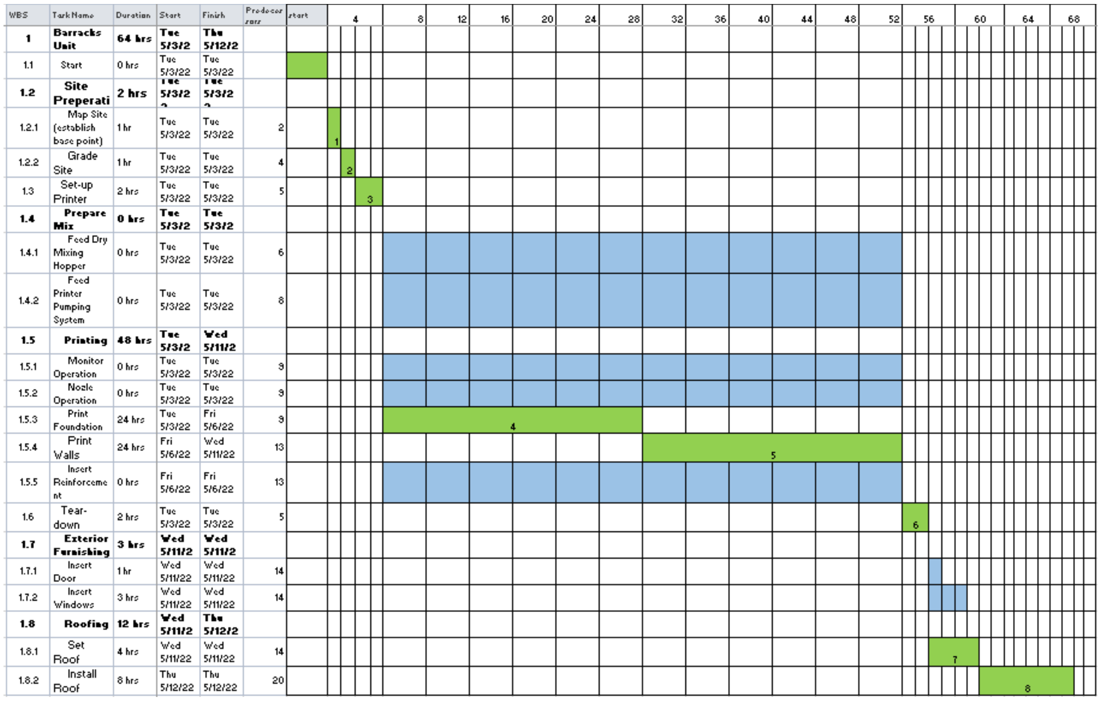
For this section of my thesis, a gap analysis was performed on CE AFSC core and diamond skills vs the skills required to perform AMC. Core skills are defined as mandatory tasks which the AFCFM has identified as a minimum qualification requirement within an AFS or duty position. These tasks exemplify the essence of the career field. Diamond tasks are the same as core tasks with one exception--equipment shortfalls at most locations have created problems with the actual hands-on training/certification of these tasks. This training will be performed and documented when equipment becomes available.

This analysis will inform the study of what skills need be added to existing CE AFSC skills to perform AMC. To begin this analysis a project WBS must be selected as a base for the construction tasks. From these construction tasks the skills required to complete said project using AMC technology can be determined. The project that was selected for this thesis is the construction of a concrete barracks unit. This project was selected because the Army Research Lab previously constructed a similar facility using AMC and this project is a reasonable expectation of application given the humanitarian application motivation discussed previously (Jagoda et al. 2021). With the project selected, the WBS was built utilizing both Microsoft (MS) Project and MS Excel. MS Project was constructed to show the relationships between tasks whereas MS Excel was used to build a simplified version of those relationships. Figures 2 and 3 respectively represent the MS Project and MS excel WBS.



Tas Mc	WBS	Task Name	Duration	Start	Finish	Predecessors
	1	**Barracks Unit**	**65 hrs**	**Tue 5/3/22**	**Fri 5/13/22**	
	1.1	Start	0 hrs	Tue 5/3/22	Tue 5/3/22	
	1.2	**Site Preperation**	**2 hrs**	**Tue 5/3/22**	**Tue 5/3/22**	
	1.2.1	Map Site (establish base p	1 hr	Tue 5/3/22	Tue 5/3/22	2
	1.2.2	Grade Site	1 hr	Tue 5/3/22	Tue 5/3/22	4
	1.3	Set-up Printer	2 hrs	Tue 5/3/22	Tue 5/3/22	5
	1.4	**Prepare Mix**	**0 hrs**	**Tue 5/3/22**	**Tue 5/3/22**	
	1.4.1	Feed Dry Mixing Hopper	0 hrs	Tue 5/3/22	Tue 5/3/22	6
	1.4.2	Feed Printer Pumping Syst	0 hrs	Tue 5/3/22	Tue 5/3/22	8
	1.5	**Printing**	**48 hrs**	**Tue 5/3/22**	**Wed 5/11/2**	
	1.5.1	Print Foundation	24 hrs	Tue 5/3/22	Fri 5/6/22	9
	1.5.2	Print Walls	24 hrs	Fri 5/6/22	Wed 5/11/2	11
	1.5.3	Insert Reinforcement	0 hrs	Fri 5/6/22	Fri 5/6/22	11
	1.6	Tear-down Printer	1 hr	Wed 5/11/2	Wed 5/11/2	12
	1.7	**Exterior Furnishing**	**3 hrs**	**Wed 5/11/2**	**Wed 5/11/2**	
	1.7.1	Insert Door	1 hr	Wed 5/11/2	Wed 5/11/2	14
	1.7.2	Insert Windows	3 hrs	Wed 5/11/2	Wed 5/11/2	14
	1.8	**Roofing**	**12 hrs**	**Wed 5/11/2**	**Fri 5/13/22**	
	1.8.1	Set Roof Trusses	4 hrs	Wed 5/11/2	Thu 5/12/22	14
	1.8.2	Install Roof Panels	8 hrs	Thu 5/12/22	Fri 5/13/22	19

Figure 2: Microsoft Project Work Breakdown Structure



WBS	Task Name	Duration	Start	Finish	Predecessors
1	**Barracks Unit**	**64 hrs**	**Tue 5/3/2**	**Thu 5/12/2**	
1.1	Start	0 hrs	Tue 5/3/22	Tue 5/3/22	
1.2	**Site Preperati**	**2 hrs**	**Tue 5/3/2**	**Tue 5/3/2**	
1.2.1	Map Site (establish base point)	1 hr	Tue 5/3/22	Tue 5/3/22	2
1.2.2	Grade Site	1 hr	Tue 5/3/22	Tue 5/3/22	4
1.3	Set-up Printer	2 hrs	Tue 5/3/22	Tue 5/3/22	5
1.4	**Prepare Mix**	**0 hrs**	**Tue 5/3/2**	**Tue 5/3/2**	
1.4.1	Feed Dry Mixing Hopper	0 hrs	Tue 5/3/22	Tue 5/3/22	6
1.4.2	Feed Printer Pumping System	0 hrs	Tue 5/3/22	Tue 5/3/22	8
1.5	**Printing**	**48 hrs**	**Tue 5/3/2**	**Wed 5/11/2**	
1.5.1	Monitor Operation	0 hrs	Tue 5/3/22	Tue 5/3/22	9
1.5.2	Nozle Operation	0 hrs	Tue 5/3/22	Tue 5/3/22	9
1.5.3	Print Foundation	24 hrs	Tue 5/3/22	Fri 5/6/22	9
1.5.4	Print Walls	24 hrs	Fri 5/6/22	Wed 5/11/22	13
1.5.5	Insert Reinforcement	0 hrs	Fri 5/6/22	Fri 5/6/22	13
1.6	Tear-down	2 hrs	Tue 5/3/22	Tue 5/3/22	5
1.7	**Exterior Furnishing**	**3 hrs**	**Wed 5/11/2**	**Wed 5/11/2**	
1.7.1	Insert Door	1 hr	Wed 5/11/22	Wed 5/11/22	14
1.7.2	Insert Windows	3 hrs	Wed 5/11/22	Wed 5/11/22	14
1.8	**Roofing**	**12 hrs**	**Wed 5/11/2**	**Thu 5/12/2**	
1.8.1	Set Roof	4 hrs	Wed 5/11/22	Wed 5/11/22	14
1.8.2	Install Roof	8 hrs	Thu 5/12/22	Thu 5/12/22	20

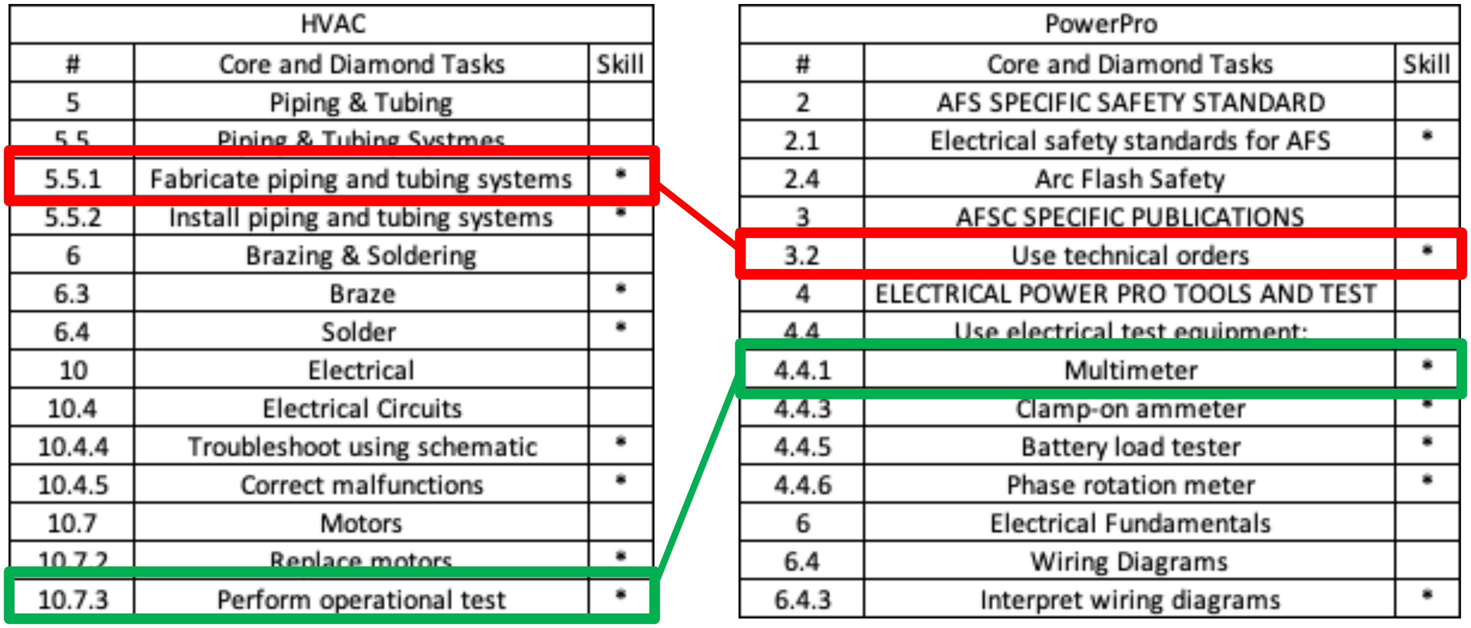
Figure 3: Microsoft Excel Work Breakdown Structure

Figure 3 shows the primary task elements in green blocks with their time step listed on them. This time step represents a block of time for a task that is used in the team selection model as opposed to using the number of hours for each task. The blue task elements represent other tasks that occur in support of the critical task construction elements. With the tasks defined in the WBS and the primary gap being identified as specific equipment training, the next step was to determine the skills of each CE AFSC enabling later assignment to tasks.

To determine the set of skills that each CE AFSC has Career Field Education and Training Plans were consulted. Within each of the documents, Air Force Qualification Training Packages (AFQTP) were consulted and those Core and Diamond skills required to be qualified in said AFSC defined. Those Core and Diamond skills are skillsets used for this research. See Appendix A: 3E0X1 Core and Diamond Skills Table Excerpt for a partial example of the CE AFSC Core and Diamond skills tables used in this research. The full table for each AFSC AFQTP can be found on CE DASH under documents in the AFQTP folder. These skills are used to determine which AFSC has the skill to complete each of the different construction tasks outlined in the project WBS. Additionally, these skills were used as the basis of the MCA training analysis data (discussed in the following section) to be used in the personnel team optimization model presented in Chapter IV.

CE AFSC Skills Comparison Analysis

With each of the CE AFSC Core and Diamond tasks determined a cross comparison of each of those skillsets was completed to determine the percentage of skill overlap between each of these AFSCs. This analysis drives toward building a parameter for an AF CE MCA which is implemented in the Team Selection model. To perform this analysis each AFSC AFQTP Core and Diamond Task list was compared line by line (task by task) to each other list for all eight AFSCs considered in this study. A visualization of this comparison is depicted in Figure 4.



HVAC		
#	Core and Diamond Tasks	Skill
5	Piping & Tubing	
5.5	Piping & Tubing Systmes	
5.5.1	Fabricate piping and tubing systems	*
5.5.2	Install piping and tubing systems	*
6	Brazing & Soldering	
6.3	Braze	*
6.4	Solder	*
10	Electrical	
10.4	Electrical Circuits	
10.4.4	Troubleshoot using schematic	*
10.4.5	Correct malfunctions	*
10.7	Motors	
10.7.2	Replace motors	*
10.7.3	Perform operational test	*

PowerPro		
#	Core and Diamond Tasks	Skill
2	AFS SPECIFIC SAFETY STANDARD	
2.1	Electrical safety standards for AFS	*
2.4	Arc Flash Safety	
3	AFSC SPECIFIC PUBLICATIONS	
3.2	Use technical orders	*
4	ELECTRICAL POWER PRO TOOLS AND TEST	
4.4	Use electrical test equipment:	
4.4.1	Multimeter	*
4.4.3	Clamp-on ammeter	*
4.4.5	Battery load tester	*
4.4.6	Phase rotation meter	*
6	Electrical Fundamentals	
6.4	Wiring Diagrams	
6.4.3	Interpret wiring diagrams	*

Figure 4: AFSC AFQTP Comparison Analysis

Figure 4 displays how tasks are compared and likeness or unlikeness is determined for each task. The green and red connections do not display exact similarity or dissimilarity but rather how the process was completed. If one task was similar to another then a 1 was recorded because this would mean the AFSC in question could complete the task of the AFSC it was being compared too. Only the tasks with a mark in the skill column were recorded as these are the skills that make up the Core and Diamond skills for each AFSC.

The line-by-line comparison of each of these tasks was performed using a binary system. When similar tasks were displayed the AFSC would get a 1 on that line representing that the AFSC has the training to complete the other AFSCs task. This system was summed after the full comparison and that sum was divided by the total number of tasks of the other AFSC to determine the percent likeness between AFSCs.

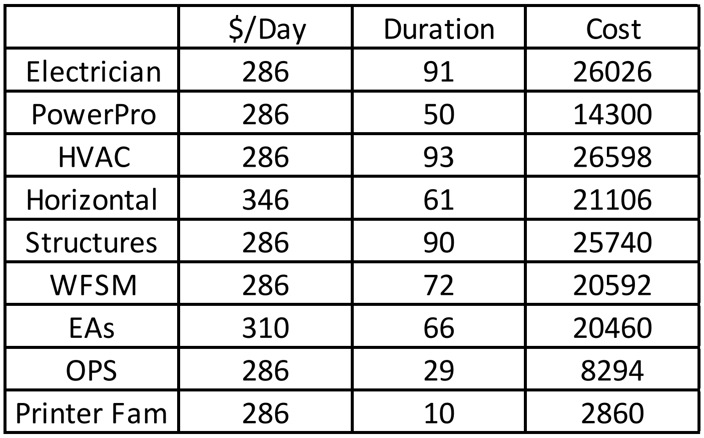
Because each AFSC AFQTP was a different number of tasks a one-way analysis wouldn’t work thus this process was completed for all 56 AFSC comparisons. These percent likeness results are reported in Table 4.

Table 4: AFSC AFQTP Percent Likeness Analysis

	% Likeness							
	HVAC	PowerPro	Heavy	Structures	Eas	OPS	WFSM	Electrician
HVAC	1.000	0.020	0.020	0.000	0.000	0.024	0.106	0.011
PowerPro	0.091	1.000	0.006	0.037	0.000	0.000	0.094	0.096
Heavy	0.000	0.000	1.000	0.074	0.000	0.073	0.035	0.011
Structures	0.000	0.000	0.109	1.000	0.000	0.000	0.024	0.011
Eas	0.000	0.000	0.026	0.000	1.000	0.268	0.071	0.032
OPS	0.000	0.000	0.006	0.000	0.012	1.000	0.000	0.032
WFSM	0.136	0.050	0.032	0.056	0.000	0.000	1.000	0.074
Electrician	0.091	0.120	0.013	0.019	0.035	0.195	0.200	1.000

These results represent the percentage of training overlap between AFSCs one of the parameters used to develop a cost parameter for a CE AFSC MCA. Table 4 should be read from AFSC on the left has x amount of similarity when compared to AFSC on the top. For example, HVAC (on the left) can do 2% of the tasks that PowerPro (on the top) can do based on a comparison of their AFQTPs. This percent likeness analysis is then used in combination with Enlisted Initial Skills (EIS) cost data for each AFSC to develop the final MCA cost parameter shown in Table 6. EIS cost and duration data is displayed in Table 5. This cost per day and total duration of training data was pulled from AFCEC EIS trainers.

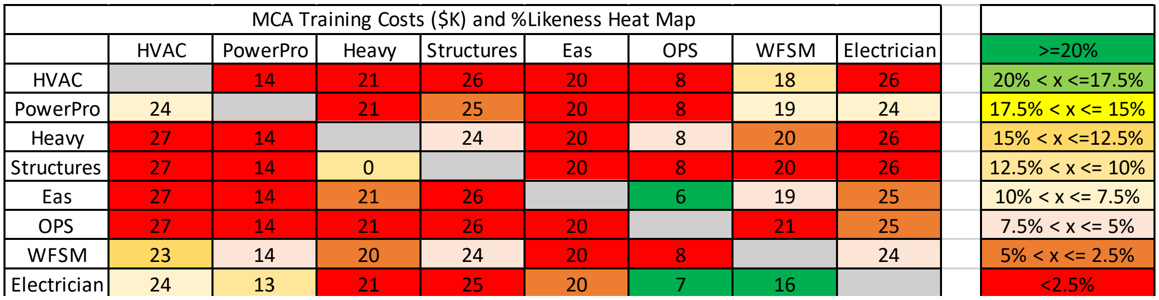
Table 5: AFSC EIS Cost Data



	$/Day	Duration	Cost
Electrician	286	91	26026
PowerPro	286	50	14300
HVAC	286	93	26598
Horizontal	346	61	21106
Structures	286	90	25740
WFSM	286	72	20592
EAs	310	66	20460
OPS	286	29	8294
Printer Fam	286	10	2860

AFQTP critical and diamond tasks were selected as the foundational skill data for this research based on the assumption that the AF would likely want to ensure an Airmen can be proficient in one AFSC before expecting them to be proficient in multiple AFSCs. Meaning, an MCA qualifier would likely be attached to 5 or 7 level airmen rather than training a brand-new airman just out of technical school. Along with that assumption comes one key limitation of how the cost parameter for MCA was built. Data on the durations and costs for this AFQTP upgrade training is very limited. There may be standards within shops but quantifiable data on this upgrade training in terms of cost and duration in relation to MCA is currently unavailable. Due to this limited and or non-existent MCA data, the cost data from EIS was selected as the best currently available cost to training AFSC data and was used to develop the final cost parameter displayed in Table 6. More about this limitation will be discussed in Chapter VI of this document.

Table 6: Multiple Capable Airmen Training Costs and Percent Likeness Heat Map



MCA Training Costs ($K) and %Likeness Heat Map

	HVAC	PowerPro	Heavy	Structures	Eas	OPS	WFSM	Electrician
HVAC		14	21	26	20	8	18	26
PowerPro	24		21	25	20	8	19	24
Heavy	27	14		24	20	8	20	26
Structures	27	14	0		20	8	20	26
Eas	27	14	21	26		6	19	25
OPS	27	14	21	26	20		21	25
WFSM	23	14	20	24	20	8		24
Electrician	24	13	21	25	20	7	16	

>=20%
20% < x <=17.5%
17.5% < x <= 15%
15% < x <=12.5%
12.5% < x <= 10%
10% < x <= 7.5%
7.5% < x <= 5%
5% < x <= 2.5%
<2.5%

Table 6 represents a heat map showing both cross training cost displayed numerically and percent likeness between AFSCs displayed in color. To be expected, CE AFSCs each do drastically different things and thus the percent likeliness between CE AFSCs is very minute. The largest overlap in training happens between EAs and Ops and Electricians and OPS and WFSM. Of those three the largest is only a 26% overlap. What this shows is that based on AFSC AFQTP in order to be certified as a MCA AFSCs would have to complete nearly all of another AFSCs upgrade training to reach that 5-7 level proficiency. This means that, from a cost perspective, there may likely be little to no value to a MCA in AF CE. These results represent the final MCA cost parameter to be used in the AMC personnel UTC optimization model presented in Chapter IV.

IV. Additive Manufacturing Construction Personnel UTC Optimization

Chapter Overview

This chapter summarizes the approach taken to complete the Personnel UTC Optimization portion of this research. An optimization problem was built to minimize the cost of completing the barracks unit 3-D printed construction project based on the previously mentioned WBS. The formulation of this optimization problem was developed using the GAMs coding software with excel data being pulled in using the xls2gms call function. The code was written using a base of Sets, Parameters, Constraints and a single Decision Variable (DV) to optimize the resulting team based on the input data. The specifics behind this model, the methods and the results are reported in the following sections.

The Optimization Model

For this section of the thesis, the goal is identifying an AFSC team composition that is optimized based on skills and tasks required to execute construction in an expeditionary environment. AMC is not unlike CC but the existing differences are significant enough that specialized training is required to achieve proficiency. There are two main pieces to this optimization problem, the first is that skills of personnel are matched with skills required for the tasks and second is that the team is as light/lean as possible with no duplicative skills. To do this, an optimization problem was developed to minimize the cost of each of these two components. There is a cost associated with a certain AFSC completing a task based on the skill they have and those they could have based on additional training and a cost associated with a certain AFSC selected to be on the team in the first place. A breakdown of the formulation is as follows.

Let $\mathcal{I}$ be set of personnel, each with a unique AFSC. The set of AFSCs used in this model is composed of Electrician, PowerPro, HVAC, Horizontal, Structures, WFSM, EAs and Ops. Let $\mathcal{J}$ be a set of finite skills. The set of finite skills required based on the tasks in the WBS are as follows: Operate_Heavy_Equip, Mapping, Concrete_Fam, 3D_Printer_Software, Printer_Operations, Concrete_Finishing, Structural_Wood_Working, Roofing, Printer_Monitor_Op, Nozel_Op and General. Each of these skills must be met by whichever AFSC is assigned to a given task that requires said skill. Let $\mathcal{N}$ be a set of tasks defined by the WBS. The set of tasks determined to be required for project completion are as follows: Map_Site, Grade_Site, Printer_Setup, Mix_Concrete, Feed_Pump_System, Print_Foundation, Print_Walls, Insert_Reinforcement, Printer_Tear_Down, Insert_Door, Insert_Windows, Set_Roof_Trusses, Install_Roof_Panels, General, General2. Finally, let $\mathcal{T}$ be a set of time intervals in which tasks are aligned in the WBS. Based on the given WBS for the barracks unit, the set of time intervals for this project is determined to be 1-8. This model is built upon task intervals rather than task durations. This enables the model to assign one individual per task interval rather than at each time interval. These are the four sets built into the model.

Let x_{int} be the single integer variable this model is trying to solve for. This variable represents the assignment of an AFSC i being assigned to task n at time interval t. Any of the set of AFSCs could be assigned to any task at any time based on the optimization model.

Let r_{njt} be a binary parameter that assigns when task n requires skill j at time t. This parameter is built as a binary to state that at a specific time on the project, a specific task needs to be completed and that task requires a specific skill. See Appendix A: Task n Requiring Skill j at Time t for a full breakdown of the task and skill combinations required at specific time steps during the project. Let s_{ij} be a binary parameter that establishes if AFSC i has skill j. This optimization problem utilizes the multiple capable airmen concept thus one of the main assumptions going into building the skill table for this model is that any AFSC can learn the skills of another AFSC it will just cost money to do so. The optimization will look to both minimize the number of personnel (cost associated with a member being on the team) and the amount of cost required for a selected AFSC to perform a selected task. Let c_{in} be a cost associated with AFSC i performing task n. In order for each AFSC to have all the skills required to complete any task a cost table was developed detailing the training costs that would be incurred to enable that AFSC to complete said tasks. See Appendix A: Cost of AFSC (i) Completing Task (n) for costs that would be incurred to give each AFSC the training required to perform said tasks. Because the majority of these trainings are completed based on an individual basis and training cost data is not readily available EIS training duration and cost was used. Cost per day and total duration data for each EIS was obtained via Air Force Civil Engineer Center (AFCEC) training program managers to be used in the model. See Table 5 for EIS cost and duration data. These costs are applied to each member of each AFSC regardless of which iteration is being considered. Finally, let z_i be a cost associated with AFSC i being on the team. The cost for any AFSC being selected to be on the team is denoted by their Total Cost column denoted in Table 5.

This model utilizes two scalars. $U \; and \; L$, representing a maximum and minimum number of personnel required for the project. These Sets, Parameters, Scalars and Variable are detailed in Table 7.

Table 7: Team Optimization Model Notation

	Identifier	Description	Index
Sets	$\mathcal{I}$	Set of personnel AFSCs	i
	$\mathcal{J}$	Set of finite skills	j
	$\mathcal{N}$	Set of tasks	$n = \{1, \dots, N\}$
	$\mathcal{T}$:	Set of time intervals	$t = \{1, \dots, T\}$
Variable	x_{int}	Assignment of personnel i to task n at time interval t	i, n, t
Parameters	r_{njt}	Binary when task n requires skill j at time interval t	n, j, t
	s_{ij}	Binary when AFSC i has skill j	i, j
	c_{in}	Cost for AFSC i to perform task n	i, n
	z_i	Cost for AFSC i to be on the team	i
Scalars	U	Maximum number of personnel	
	L	Minimum number of personnel	

Objective Function for 3 Per AFSC UTC Team:

Minimize $\sum_{i\in\mathcal{I}} \sum_{n\in\mathcal{N}} \sum_{t\in\mathcal{T}} c_{in} x_{int} + \sum_{i\in\mathcal{I}} \sum_{n\in\mathcal{N}} \sum_{t\in\mathcal{T}} z_i x_{int}$ (1)

S.T. 1) Maximum number of personnel (There has to be some cap on the number of personnel)

$u \leq \sum_{i\in\mathcal{I}} \sum_{n\in\mathcal{N}} x_{int} \; \forall t \in \mathcal{T}$ (2)

2) Minimum number of personnel (2 personnel is the minimum number of personnel that can operate any AMC printer)

$l \geq \sum_{i\in\mathcal{I}} \sum_{n\in\mathcal{N}} x_{int} \; \forall t \in \mathcal{T}$ (3)

3) Number of personnel is >= 0 (non-negativity, there must be more then 0 personnel)

$x_{itn} \geq 0, \ \forall i \in \mathcal{I}, n \in \mathcal{N}, t \in \mathcal{T}$ (4)

4) A person can only work on one task per any single time interval. This constraint means that a single person cannot be working on two things at the same time.

$\sum_{n \in \mathcal{N}} x_{int} \leq 1 \ \forall i \in \mathcal{I}, t \in \mathcal{T}$ (5)

5) All skill requirements to execute each of the tasks must be met.

$\sum_{i \in \mathcal{I}} x_{int} = \sum_{j \in J} r_{njt} \ \forall n \in \mathcal{N}, t \in \mathcal{T}$ (6)

This model was developed and objective function tested for three sets of AFSC team compositions. Those compositions being two of each AFSC, 3 of each AFSC and using the 4FPET team construct minus the 32E position. The formulation for each iteration was the same with the exception of updating both the GAMs code and the excel data tables for each separate list of AFSCs. A “How to Use and or Update” document can be found in Appendix B. Taking this approach allows for the understanding of if developing a specifically tailored personnel UTC could have cost advantages over using an existing 4FPET UTC (also using a multiple capable airman concept). The results of these models can be found in the following sections of this chapter.

Optimization Results

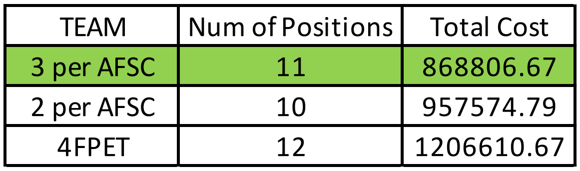
For this section of the thesis, the results of the optimization model will be reported for each of the three team compositions tested. The model output reports what AFSC position is assigned to what task at what time for all tasks. The results of the output for the 3 per AFSC model are reported in Table 8.

Table 8: X(i,n,t) AFSC i on Task n at Time Interval t

i(AFSC)	.	n(Task)	Time Period							
			1	2	3	4	5	6	7	8
PowerPro3	.	Set_Roof_Trusses							1	
Horizontal1	.	Grade_Site		1						
Horizontal1	.	Print_Foundation				1				
Horizontal1	.	Print_Walls					1			
Horizontal2	.	Print_Foundation				1				
Horizontal2	.	Insert_Reinforcement					1			
Horizontal3	.	Mix_Concrete					1			
Horizontal3	.	Print_Foundation				1				
Structures1	.	Printer_Setup			1					
Structures1	.	Print_Walls					1			
Structures1	.	Insert_Reinforcement				1				
Structures1	.	Printer_Tear_Down						1		
Structures1	.	Set_Roof_Trusses							1	
Structures1	.	Install_Roof_Panels								1
Structures2	.	Printer_Setup			1					
Structures2	.	Mix_Concrete				1				
Structures2	.	Feed_Pump_System					1			
Structures2	.	Printer_Tear_Down						1		
Structures2	.	Set_Roof_Trusses							1	
Structures2	.	Install_Roof_Panels								1
Structures3	.	Printer_Setup			1					
Structures3	.	Feed_Pump_System				1				
Structures3	.	Printer_Tear_Down						1		
Structures3	.	Insert_Door							1	
EAs1	.	Map_Site	1							
Ops1	.	General	1	1			1			1
Ops1	.	General2			1	1		1	1	
Ops2	.	General			1	1		1	1	
Ops2	.	General2	1	1			1			1
Ops3	.	Insert_Windows							1	

The decision variable reported in Table 8 is a binary variable where a 1 represents that the AFSC is on that task in that time interval. This composition of AFSCs on tasks represents the full construction capability over the 8 time periods that compose the WBS. This output is reported for each of the three team compositions and the other two can be found in Appendix A: 2 Per AFSC and 4FPET Team Composition Model Outputs. Finally, the model also reports the total cost of completing this construction based on the personnel assigned. Table 9 displays the number of positions and total cost of the team to perform all tasks in the WBS.

Table 9: Optimization Model Final Cost and Number of Positions



TEAM	Num of Positions	Total Cost
3 per AFSC	11	868806.67
2 per AFSC	10	957574.79
4FPET	12	1206610.67

Based on the three team compositions tested with this model, the least cost option was the 3 per AFSC team composition which was made up of 1 Power Production, 3 Horizontal, 3 Structures, 1 Engineering Assistant and 3 Operations Engineers. This team composition resulted in a total cost of $868,806.67 to complete the barracks unit construction via 3-D printed construction. The costs of utilizing the 2 per AFSC model or the 4FPET team composition resulted in the total costs reported in Table 9.

The final factor to consider with these team compositions is personnel utilization rate. Utilization rate is the amount of productive work hours out of the total work period. In this case the total project work hours as determined through the WBS is 66hrs. Each positions utilization rate was determined by taking their total task time over the project duration. Utilization rates for each of the three team compositions tested with this model are reported in Figure 5. The important result taken from this is that a full 4FPET team is not required to perform the construction of this barracks unit utilizing AMC technology. In fact, 13 of the 25 total positions aren't utilized at all. This displays that there is some composition of team members that have a more efficient utilization then if a 4FPET team was tasked to perform this construction. Based on the cost results of the model, the 3 per AFSC team produced the least cost while having a slightly worse overall utilization then the 2 per AFSC model, but both have a significantly better utilization then the PET team.

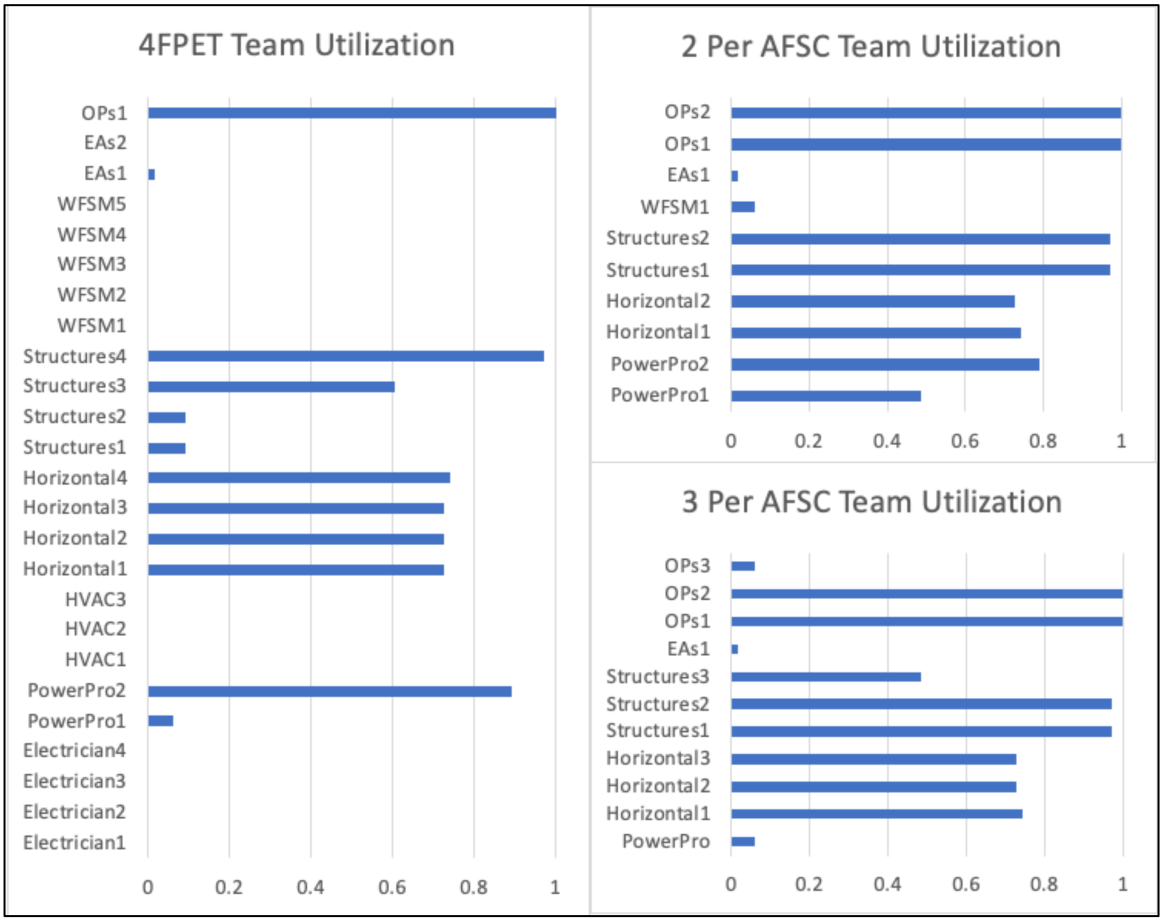


Figure 5: Team Selection Model Utilization Rates Per Individual Team Members

These utilization and cost results indicate that the model may be able to find a smaller, better utilized team that may cost more due to more multiple-capable airmen training. If the goal for the team that is being built is to be a minimum number of personnel the parameter for maximum number of personnel could be adjusted. In this case, based on the work breakdown structure, a minimum number of personnel required is eight thus by adjusting the max personnel parameter a smaller team would be output. This team may cost more to assembly and meet all skill requirements but it would be minimized based on number of personnel.

Project Management Golden Triangle

For this section of the thesis, the golden triangle of project management how it effects a project and how each of the three qualities will be covered under this research methodology will be covered. The three components of the golden triangle are scope, cost and schedule all of which effect the success/quality of a project. Each of these components were introduced in this model through the WBS, the training and the model optimization problem. The initial goal of this research was to perform construction with a higher priority on cost so by developing a model that has a goal of the reduction of cost based on its given parameters, overall cost becomes a primary piece of the model. Both schedule and scope become fundamental components of the model through the WBS. The WBS defines both the scope of the project through each of its individual tasks and the schedule thorough the planning of those tasks leading to an overall project duration. Each of these model features, including the emphasis placed on team competency through training impacts the overall quality of the project. By developing the model in this way, the fundamental importance of cost, scope, schedule and quality can be met in AF construction through the use of AMC.

Model Limitations

One primary limitation to this model is the personnel cost associated with project duration. The model accounts for the two primary costs associated with the team being trained and capable of performing construction but not the daily costs associated with total project duration. This factory may change the results of the model as another factor minimizing total cost of the team. As project durations increase, labor costs will increase and thus there may be more of an emphasis placed on reducing overall team size then there is under the current model.

The second limitation to this model is what happens if a team member goes down and cannot perform their job during a time period that they are assigned. Personnel not being able to complete their jobs due to unforeseen circumstances is certainly a problem that should be considered when building a team. To account for this risk, the two general positions were assigned for the duration of the project. These positions do not necessarily have specific tasks throughout the duration but they are there to be available as floaters and given a down body said floater may be able to fill in for that task in that time.

V. AMC Printer Selection Analysis

Chapter Overview

This chapter summarizes the approach taken to complete the 3-D Printer Selection Process portion of this research. This equipment selection process is composed of three primary components, determining printer selection criteria, determining the right weighting structure for those criteria and determining how each printer being analyzed meets those criteria based on utility. Each of these three components and their methods will be further detailed in the following sections leading to the resulting best fit printer for application in Air Force Expeditionary Engineering.

Market Analysis

There are a multitude of different AMC printers readily available on the market and some that are not readily available but are currently in use by other organizations. Those printers all have different styles, specifications and use scenarios that make each viable in their own way. One of the objectives of this thesis is to analyze several of these options and through the use of AHP and MAUT select a best fit printer for the Air Force Expeditionary Construction. Five printers were analyzed for this thesis. Those five were selected from a surface level investigation on what printers are currently being used and which appear to be most viable. The list of these printers and their technical specifications for each of the eight criteria are displayed in Table 10. One caveat captured in this process was including both Gantry style and Robotic Arm style printers as although they do the same thing, they both have significant pros and cons as discussed in the Gantry vs Robotic Arm Printer Style section in the Literature Review Chapter of this thesis.

Table 10: 3-D Printer Criteria Data

	Aces Lite	BOD2	MAXI	Mudbots	StroyBot
Set-Up Time	1hr, jacks for quick leveling	4-6 hours concrete base plates	2 hrs, self leveling legs	2-3hrs (baseplates)	1hr
Cost ($K)	<~1000	750	550	550	950
Use of Local Materials	YES	NO (Pre-mix)	No (Pre-mix)	YES (part of their training is teaching you how to create mixes that work for you)	Additives required but mixes based on sand and cement
Use Complexity	simple/no proprietary mix	Medium/pre-mix/concrete footers	Medium/pre-mix, 3-D or 2-D, small robotic arm	simple/no proprietary mix	simple/no proprietary mix
Dismantalable (How is it shipped)	Shipped in 20ft ISO	Tractor trailer can be broken down into shippable sized pieces	Shipped in 20ft ISO	tractor trailer/tailored tear down	Shipped in 20ft ISO
Durability	very good	very good	More mechanical	very good	very good
Maintainability	very good	very good	More mechanical	very good	very good
Build Size (m3)	10x3x4	7x9x4	12x12x7 (circle diameter not like gantry)	7x8x4	10 x 20 x 4
Style	Gantry	Gantry	Arm on track	Gantry	Gantry
Operators	3 people	2 people - 4	2 people	2 people	2-3 people

Analytical Hierarchy Process

This process of weighting and hierarchy building is subjective in nature and is a limitation of this process. The next person to design this hierarchy may build it differently leading to a different result. To prevent this, it is important for decision makers to represent the problem as thoroughly as possible. The evaluation is also affected by the subjective judgments of decision makers. Even though two decision makers structure the same hierarchy, their different judgments may yield different priority weights (Lee 2014). To help make the AHP design and weighting as objective as possible, an expert elicitation was conducted to determine the importance weighting for each criterion to be used in the AHP.

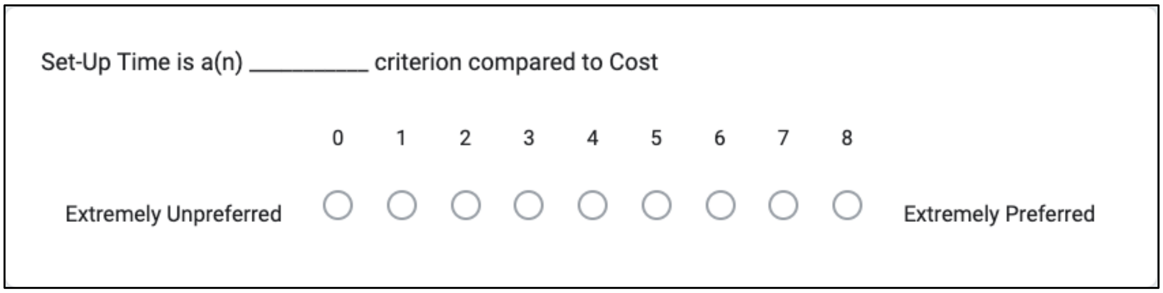
Due to the subjective nature of AHP it is important to gather data from multiple decision makers that may eventually use the results of this work. To do so, a questionnaire prompting the comparison of each of the eight criteria was developed to be completed by each of these decision makers. Before the elicitation was sent to participants a pilot study was executed by multiple individuals to ensure it was ready for distribution. Several small errors were identified, corrected and the elicitation was finalized for distribution. Participants in the expert elicitation where selected based on their subject matter expertise or high-level leadership position within the Air Force Civil Engineer Center. The primary targets for this elicitation were in the AFCEC Expeditionary Engineering division whom are either leaders making important CE decisions or personnel currently working on AF initial utilization of 3-D printed construction.

The baseline of criterion importance relative to each other is established using the scale defined in Table 11. An example question displaying how the scale appears to participants is displayed in Figure 6. This scale was developed for ease of use for each of the participants and scores later converted to match the AHP importance scale in Table

11. The full questionnaire can be accessed at AMC Printer Selection Criteria. The importance values of each individual's criterion ratings were averaged to find a single importance value for each criterion. Those values were then converted to numerical ratings on the scale of 1 to 9 presented in Table 12.

Table 11: Expert Elicitation Criteria Comparison Scale

Scale	Numerical Rating
Extremely Unpreferred	0
Very Strongly Unpreferred	1
Strongly Unpreferred	2
Moderately Unpreferred	3
Equally Preferred	4
Moderately Preferred	5
Strongly Preferred	6
Very Strongly Preferred	7
Extremely Preferred	8



Set-Up Time is a(n) _________ criterion compared to Cost

	0	1	2	3	4	5	6	7	8	
Extremely Unpreferred	○	○	○	○	○	○	○	○	○	Extremely Preferred

Figure 6: Expert Elicitation Example Question

Table 12: AHP Criterion Importance Scale

Scale	Numerical Rating	Reciprocal
Extremely Preferred	9	1/9
Very Strong to Extremely	8	1/8
Very Strongly Preferred	7	1/7
Strongly to Very Strongly	6	1/6
Strongly Preferred	5	1/5
Moderately to Strongly	4	1/4
Moderately Preferred	3	1/3
equally to moderately	2	1/2
Equally Preferred	1	1

The final averaged criterion importance ratings to be used in this analysis are displayed in Table 13. With the importance of each criterion established, the AHP can be tested to ensure consistency among ratings. The process for determining consistency among criteria weightings will be discussed in the following section. These methods will ensure the printer selection results are valid.

Table 13: Analytical Hierarchy Process Original Criteria Weights

	Set-Up Time	Cost	Use of Local Materials	Use Complexity	Dismantalable	Durability	Maintainability	Build Size
Set-Up Time	1	4.25	0.75	0.67	0.33	0.33	0.67	1.25
Cost	1/4	1	1.00	0.75	0.92	0.58	0.58	0.75
Use of Local Materials	1 1/3	1	1	2.50	2.75	4.00	3.50	4.00
Use Complexity	1 1/2	1 1/3	2/5	1	2.00	2.50	1.25	2.25
Dismantalable	3	1	1/3	1/2	1	1.50	1.25	3.00
Durability	3	1 5/7	1/4	2/5	2/3	1	1.75	2.75
Maintainability	1 1/2	1 5/7	2/7	4/5	4/5	4/7	1	2.75
Build Size	4/5	1 1/3	1/4	4/9	1/3	1/3	1/3	1

Now that the criterion importance has been established the next piece is to determine the weights of each of these criteria. These criteria weightings were found using the nth root method. The nth root method is seen as a very good method for establishing criterion weights and is used in problems with multiple considerations such as this one. The nth root method is conducted by multiplying together the entries in each row of the matrix and then taking the nth root of that product. This method gives a very good approximation. The nth roots are summed and that sum is used to normalize the eigenvector elements to add to 1.00 (Kunz 2010). The last piece to ensuring these weights are sufficient is determining if they are consistent and one weight doesn't counteract another. Specifically, what this aims to do is make sure that if both the Law of Transitivity and Cardinal Consistency are maintained in this criteria weighting. Transitivity is ensuring that if criteria A is more important than criteria B which is more important than criteria C, we cannot at some point say that criteria C is more important than criteria A. Cardinal Consistency is that if A is two times as important as B which is 2 times as important than C then A must be four times as important as C. To do this the following "Check for Consistency of Pair-wise Comparison Matrix" steps are executed.

Check for Consistency of Pair-wise Comparison Matrix $[A]_{nxn}$:

1) Check for Transitivity
    a. If A is preferred to B & B is preferred to C.
    b. Then A must be preferred to C.
2) Check for Cardinal Consistency
    a. If A is twice as preferred to B & B is twice as preferred to C
    b. Then A must be four times as preferred then C
3) The matrix maximum eigen value $\lambda_{max} \geq n$
4) Perfect consistency occurs when $\lambda_{max} = n$
5) Departure from consistency = $\lambda_{max} - n$
6) Consistency Index (CI) represents deviation from perfect consistency
7) CI = $(\lambda_{max} - n)/(n - 1)$
8) Perfect consistency occurs when CI = 0

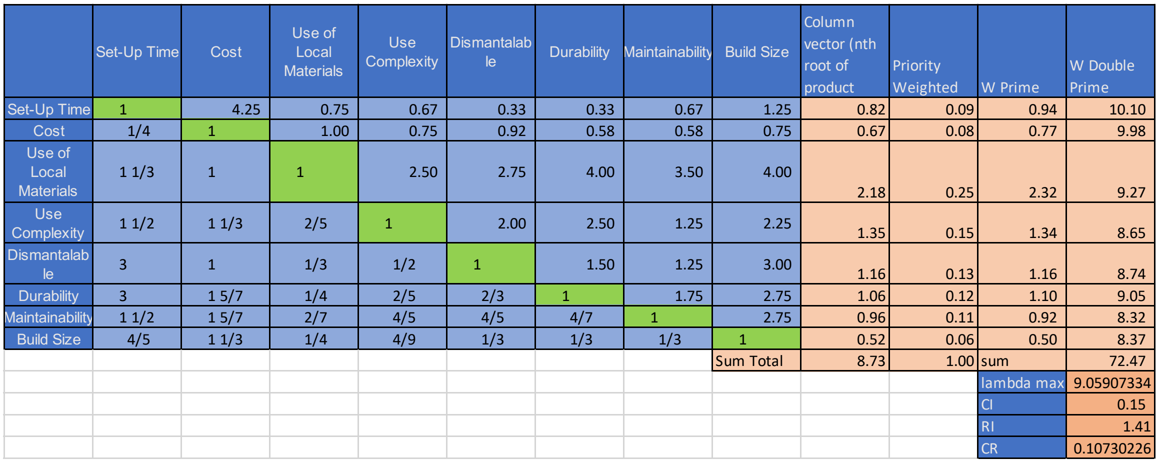
9) Complete inconsistency occurs in a randomly generated reciprocal matrix that utilizes a scale of 1 to 9
10) CI of a randomly generated matrix is called Random Index (RI)
11) The close the CI value to RI value means higher inconsistency
12) For acceptable consistency, the Consistency Ration (CR) = CI/RI must be less than or equal to 0.1
13) For a randomly generated matrix, the RI values are calculated for various sizes of n as seen in Table 14

Table 14: Random Index Values for Various n Sizes

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.53	1.56	1.57	1.59

Utilizing the nth root method valid consistency among weights occurs when the resulting consistency ration is less then 0.10 Table 15 displays the consistency ratio from the original criteria weights. With a CR of 0.107 the criteria weights from the original elicitation importance ratings are determined to be inconsistent.

Table 15: Analytical Hierarchy Process Original Criteria Weights and Consistency



	Set-Up Time	Cost	Use of Local Materials	Use Complexity	Dismantalable	Durability	Maintainability	Build Size	Column vector (nth root of product	Priority Weighted	W Prime	W Double Prime
Set-Up Time	1	4.25	0.75	0.67	0.33	0.33	0.67	1.25	0.82	0.09	0.94	10.10
Cost	1/4	1	1.00	0.75	0.92	0.58	0.58	0.75	0.67	0.08	0.77	9.98
Use of Local Materials	1 1/3	1	1	2.50	2.75	4.00	3.50	4.00	2.18	0.25	2.32	9.27
Use Complexity	1 1/2	1 1/3	2/5	1	2.00	2.50	1.25	2.25	1.35	0.15	1.34	8.65
Dismantalable	3	1	1/3	1/2	1	1.50	1.25	3.00	1.16	0.13	1.16	8.74
Durability	3	1 5/7	1/4	2/5	2/3	1	1.75	2.75	1.06	0.12	1.10	9.05
Maintainability	1 1/2	1 5/7	2/7	4/5	4/5	4/7	1	2.75	0.96	0.11	0.92	8.32
Build Size	4/5	1 1/3	1/4	4/9	1/3	1/3	1/3	1	0.52	0.06	0.50	8.37
								Sum Total	8.73	1.00	sum	72.47
											lambda max	9.05907334
											CI	0.15
											RI	1.41
											CR	0.10730226

To achieve consistency among criteria weights the original data was explored to understand where the inconsistency was created. The original assumption was that the majority of individual results would be consistent and that a single result would be throwing the full average out of consistency. The results of the individual findings disproved this. Each individual's importance scores were tested with the nth root method and those results reported in Table 16. These results show that none of the participants were able to produce consistency in the criteria importance they selected. When averaged the overall consistency became significantly better than any individual result but it was still inconsistent.

Table 16: Individual Participant Consistency Ratios

Participant	Consistency
P1	0.11300819
P2	0.15605936
P3	0.29940806
P4	0.22317963
P5	0.33933378
P6	0.13019346
P7	0.14480138
P8	0.36240729

The next step to achieve consistency was to analyze the data of each question directly. After looking through the data, the ranges of each question were determined and the most outlying values of 1s and 8s were stepped in by 1 value reducing the overall question range. Starting with the 8s the CR was reduced but still not less than 0.10. Then the 1s were stepped in and a value of 0.0994 was achieved. Now that consistency was achieved the final criteria results are reported in Table 17.

Table 17: Analytical Hierarchy Process Final Criteria Weights and Consistency Verification

	Set-Up Time	Cost	Use of Local Materials	Use Complexity	Dismantalable	Durability	Maintainability	Build Size	vector (nth root of	Priority Weighted	W Prime	W Double Prime
Set-Up Time	1	4.25	0.83	0.67	0.50	0.33	0.67	1.25	0.87	0.10	0.99	9.85
Cost	1/4	1	1.00	0.75	0.92	0.58	0.58	0.75	0.67	0.08	0.76	9.79
Use of Local Materials	1 1/5	1	1	2.50	2.50	3.75	3.25	3.75	2.07	0.24	2.21	9.21
Use Complexity	1 1/2	1 1/3	2/5	1	2.00	2.50	1.25	2.25	1.35	0.16	1.35	8.64
Dismantalable	2	1	2/5	1/2	1	1.50	1.25	3.00	1.12	0.13	1.10	8.48
Durability	3	1 5/7	1/4	2/5	2/3	1	1.75	2.75	1.07	0.12	1.13	9.14
Maintainability	1 1/2	1 5/7	1/3	4/5	4/5	4/7	1	2.75	0.97	0.11	0.94	8.33
Build Size	4/5	1 1/3	1/4	4/9	1/3	1/3	1/3	1	0.52	0.06	0.51	8.39
								Sum Total	8.66	1.00	sum	71.85
											lambda max	8.98100331
											CI	0.14
											RI	1.41
											CR	0.09939243

Utility Curves

The last piece of information needed to determine which printer best meets the established criteria are the printer's utility scores. To determine which printer has the greatest utility score, utility curves for each of the criteria have been developed and can be seen in Figure 7. Utility curves are developed separately based on each criterion and which of those criteria can utilize the same curves. Depending on the criteria and how much value is gained from different levels of said criteria, several different curves such as linear, non-linear and step will be used to represent the differences in value gained from different levels of said criteria. The majority of these criteria will utilize previously developed utility curves that have been adapted to better fit each specific criterion (Kitson 2022).

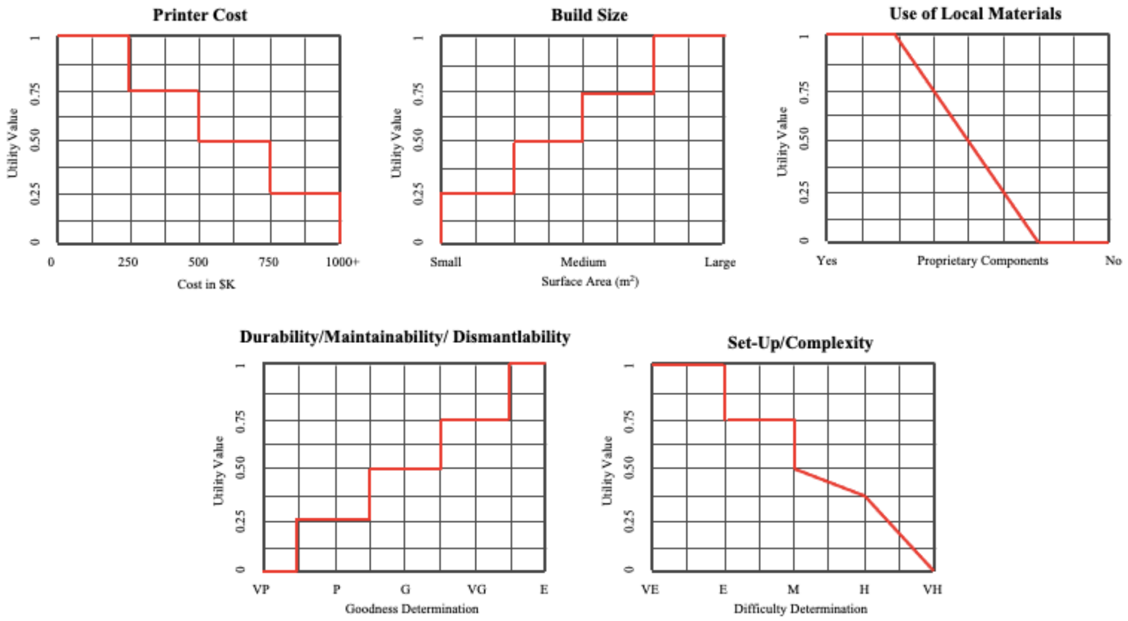


Figure 7: 3-D Printer Decision Criteria Utility Curves

Based on the printer technical specifications and the utility curves the utility values for each criterion under each printer were established. Those results are displayed in Table 18.

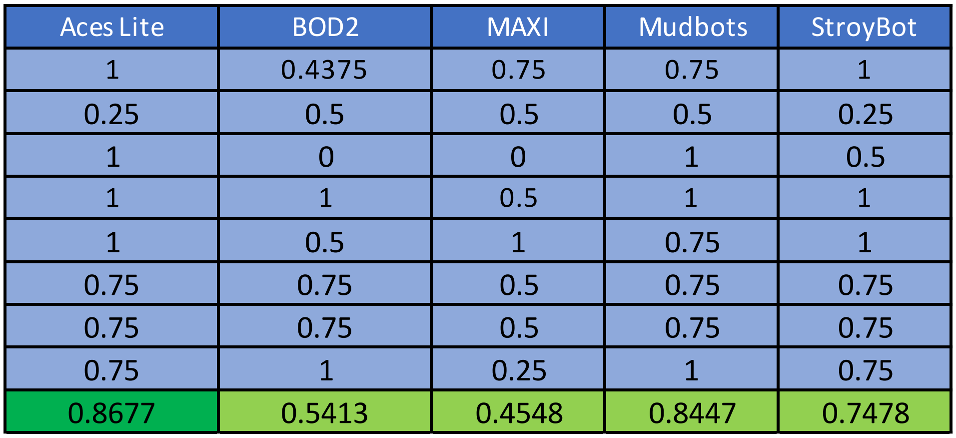
Table 18: Printer Utility Curve Determinations

	Aces Lite	BOD2	MAXI	Mudbots	StroyBot
Set-Up	VE	MH	E	E	VE
Cost	1000	750	550	550	950
Use of Local Mats	YES	NO	NO	YES	Additives
Complexity	Easy	M	Medium/High	Easy	Easy
Dismantable	Excellent	Good	Excellent	Very Good	Excellent
Durability	Very Good	Very Good	Good	Very Good	Very Good
Maintainability	Very Good	Very Good	Good	Very Good	Very Good
Build Size	Medium	Scaleable	Small	Scaleable	Medium

Best Fit Printer

Now that a consistent weighting of criteria has been confirmed and have the utility curves built, those weights can be applied to each of the different printer options and utility score to determine which has the highest score and is thus selected as the best fit for AF Expeditionary Construction. The utility score and criteria weight are multiplied together to determine a printer score for each criterion. Those scores are then summed and whichever option produces the highest score is what has been determined as the best fit printer to satisfy the given criteria. The results for the averaged weight scheme are reported in Table 19. The ACES Lite 3-D printer produces the highest utility score of 0.8677 with the Mudbots 3-D printer coming in just lower at 0.8447. Both of these printers have significantly more utility than any of the other three. Due to the inherent subjectivity of AHP these results may be sensitive to differing expert elicitation results.

Table 19: Printer Utility Scores



Aces Lite	BOD2	MAXI	Mudbots	StroyBot
1	0.4375	0.75	0.75	1
0.25	0.5	0.5	0.5	0.25
1	0	0	1	0.5
1	1	0.5	1	1
1	0.5	1	0.75	1
0.75	0.75	0.5	0.75	0.75
0.75	0.75	0.5	0.75	0.75
0.75	1	0.25	1	0.75
0.8677	0.5413	0.4548	0.8447	0.7478

To test the sensitivity of this printer selection, this analysis was conducted on each individual importance scores. These weights were not consistent thus the results are not valid themselves, however this analysis shows a sensitivity analysis of this printer selection model. The results of these individual analysis are reported in Table 20.

Table 20: Individual Expert Printer Utility Scores

	Aces Lite	BOD2	MAXI	Mudbots	StroyBot
	1	0.4375	0.75	0.75	1
	0.25	0.5	0.5	0.5	0.25
	1	0	0	1	0.5
	1	1	0.5	1	1
	1	0.5	1	0.75	1
	0.75	0.75	0.5	0.75	0.75
	0.75	0.75	0.5	0.75	0.75
	0.75	1	0.25	1	0.75
P1	0.9144	0.5754	0.4833	0.8564	0.8188
P2	0.8506	0.5796	0.4803	0.8224	0.7604
P3	0.7238	0.4802	0.3874	0.7881	0.5846
P4	0.9396	0.5231	0.4113	0.9035	0.7755
P5	0.8589	0.5546	0.5325	0.8179	0.7767
P6	0.7759	0.6791	0.5223	0.7828	0.7559
P7	0.8881	0.5778	0.5294	0.8506	0.7986
P8	0.8319	0.5727	0.4697	0.8259	0.7295

Table 20 shows that out of eight participants six individual weights selected the ACES Lite as best with the Mudbots as the runner up. The other two participants weights resulted in the Mudbots producing the highest utility values with the ACES Lite coming in a close second. This shows that in addition to the average model selecting the ACES Lite, it was also selected through importance values in 75% of individual participants. It also shows that in all eight cases either the ACES Lite or the Mudbots 3-D printer would be a good choice based on resulting utility values.

Additional Equipment Requirements

In addition to the 3-D printer itself it is important to note that the standard additional construction equipment such as hand tools and supporting heavy equipment would also be required to support this construction. The 3-D printer would do the vast majority of the structure construction, but for tasks such as roof, door or window installation hand tools and installation materials would be required. With the 3-D printer selected and supporting extra equipment the team would have all the necessary equipment to perform this construction task.

Limitations

This process of weighting and hierarchy building is subjective in nature and is a limitation of this process. If this model was built again and the weights of each printer criteria were different, the resulting best fit printer may change. Variable circumstances and rotation leaders who value different things may lead to differing priority weights and processes inevitably effecting the results of processes such as these (Lee 2014). The results also discuss how initially the criteria weighting was inconsistent and thus had to be manipulated to achieve consistency. Only 7 out of a total of 224 data points or roughly 3% of the data was manipulated but this manipulation was required to achieve consistency. This research shows that it can be difficult to achieve consistency when aggregating the results of a panel of participants. Additionally, alone, none of the participants yielded consistent weighting thus there was no singular participant that threw off the data but rather all participants. Finally, this analysis only examines a small set of 3-D printers and the addition of alternatives may also lead to a different result.

VI. Conclusions, Implications and Recommendations

Conclusions of Research

The 2018 National Defense Strategy summary outlines how strategy must adapt as the primary focus shifts to large near peer adversaries. In part, what that means for Civil Engineers is to continue delivering construction performance with a greater focus on affordability and speed. One aspect of deployed Civil Engineer squadron is to build and maintain bases, and the way that this is done currently is through means of conventional construction. This type of construction delivers the required performance but requires a significant amount of time, manpower and other resources that Civil Engineers are now being asked to be better stewards of. Reducing these necessary components of conventional construction motivates Civil Engineers to consider other construction alternatives that may yield the same result at a reduced cost of resources. For this reason, this research explored AMC as a potential alternative or supplement to conventional construction. Its implementation into the Civil Engineer expeditionary toolkit was explored to determine use cases and viability. In determining the personnel and equipment requirements for AMC implementation results including initial Civil Engineer MCA values were produced, models yielding an equipment selection methodology and team selection based on the least cost team capable of completing AMC were developed. These requirements were determined through answering the initial supporting research questions which are explained in the following sections.

The first question was, how do we determine the personnel requirements to support an additive manufacturing project? To answer this question, first, a project to be used in the model was selected and a WBS for that project was developed. With that completed, the skills required were identified and compared to the skills Civil Engineer AFSCs have. Additionally, to enable reducing labor requirements a Civil Engineer MCA concept was developed which yielded the first implementation numbers for the Civil Engineer career field. This MCA training and cost parameter was then used later used to inform the team selection model.

The second question used to determine personnel requirements was, how do we determine the right composition of personnel to support an additive manufacturing project? To answer this question, a team selection optimization model was developed using the GAMS programing language. This model was developed to find the minimum cost team capable of performing all construction tasks outlined in the WBS. The MCA cost parameter, WBS, Core and Diamond AFSC skills and different team compositions were used as inputs into the model. The model then selected the least cost team capable of performing each of the tasks in the work breakdown structure. These results showed that in terms of both utilization rate and cost, it is more beneficial to create a personnel UTC for repetitive AMC projects than utilizing the existing 4FPET team composition. Additionally, this model provides a way to quickly tailor a team based on end user requirements and specific project tasks. This model was developed with cost and number of personnel being model drivers however a similar concept for other priorities such as total duration could be developed to produce best fit teams based on other priorities.

The final question which determines the equipment requirements was, how do we determine the right AMC printer to support an additive manufacturing construction project? To answer this question an expert elicitation to determine criteria weighting was performed and a model based on existing decision-making methodologies was developed to select a best fit printer for AF expeditionary construction. The expert elicitation yielded the criteria importance weighting results used in the Analytical Hierarchy Process. A simple market analysis yielded a list of the dominant AMC printer manufactures and each of their printers to be used in the analysis. Data for each criterion for each printer was extracted and used in the selection model. Finally, Multi-Attribute Utility Theory was used to determine which printer yielded the greatest utility to the AF based on the printer's ability to meet each given criterion. This process highlighted the importance of certain criteria for AF Expeditionary Construction and the model determined that the ACES Lite printer provides the greatest utility to the AF. Finally, this process yields a robust and repeatable process for equipment selection based on end user requirements/criteria.

Implications

The primary implication of these findings is that AMC is a new technology that the AF may be able to use in conjunction with conventional construction to continue providing the desired performance but with a greater focus on resource reduction. AMC would not be fitting for all projects but for those projects that are repetitive in nature and have a semi-permanent or permanent structure requirement, it could prove a very useful technology for the AF Expeditionary Construction toolkit. These results also highlight the importance of looking into the MCA concept for AF Civil Engineers. The utilization rate results in this research show that through multiple AFSC training, minimally used AFSCs in terms of utilization rates could be minimized and overall team utilization maximized.

The model was developed in a way so that if the end user prioritizes minimizing personnel numbers over total cost, the output may be tailored to produce that result. Additionally, this model is a good baseline for how other priorities such as total time may be implement as the focus of the model rather than cost. Models such as these inform decision makers and enable them to quickly tailor a team based on the desired outcome and given inputs.

Recommended Further Research

The infancy of AMC technology allows for its use cases to be creatively determined and applied where beneficial. Both the civilian world and the Department of Defense have only just begun exploring the possibilities of 3-D printing construction which opens several doors for future research. Following are some future research topics that may be beneficial for the AF and help enable the use of this technology in the future.

First, this research has produced values for the initial implementation of the multiple capable airmen concept in the Civil Engineer career field. This concept should be further explored in conjunction with AFCEC and the Civil Engineer career field leaders to better define what it is and its use cases. A few concepts to be considered are which AFSCs should/could be combined, which AFSCs shouldn't learn the skills of others and what does this MCA training look like.

Second, this research yields an optimized team selection model based on a 500 SF barracks unit. Another research topic that could be explored and developed is furthering this team selection model by using this model for multiple different projects and creating a repository for project WBSs and optimized teams. Through the development of this repository a team optimized for ALL AMC construction projects could be selected and developed rather than individual teams for individual projects. Additionally, this repository could also store project AMC print drawings that could be asked by a team printing a structure. This could enable a potential cookie cutter select and print process to further optimize design and construction utilizing AMC.

Third, this study doesn't analyze or recommend where this printer equipment training would best be implemented. Research on where and when this training should occur could also be beneficial to the AF. For example, should it be implemented similarly to how RADR was, at Silver Flag, should it be just in time training before deployments, etc. Additionally, should this specialized capability live in base Civil Engineer squadrons or should it live as a Red Horse capability?

Fourth, this research provides theory recommendations but research into actual application will also be very beneficial. What this research could look like is working with an actual AF team to receive this training and actual print a structure. This would be something like a pilot study to analyze the viability of these concepts with Airmen who haven't previously used this equipment. In addition to the pilot study, how does this training reverberate through Civil Engineer squadrons, how would these initially trained Airmen train other Airmen and at what rate should this training occur. This will likely need to be self-sustaining and not require military members to continue getting trained by the manufacture.

Finally, certain manufactures as part of their equipment training will teach members how to make printable concrete mixes with a set of materials. One very viable option for research is analyzing the locally available materials in areas of interest across the globe and developing a printable mix based on those locally available materials for each of those areas of interest. This would help enable printing in expeditionary environments knowing that what is locally available will work. This will help to streamline these processes and reduce logistical costs and concerns with 3-D concrete construction.

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Appendix A

3 Per AFSC Optimization Model Code

```
$title a Personnel Selection Model

*here I am defining my sets
Set
t 'time intervals' / 1*8 /
n 'work tasks' / Map_Site, Grade_Site, Printer_Setup, Mix_Concrete,
Feed_Pump_System, Print_Foundation, Print_Walls,
Insert_Reinforcement, Printer_Tear_Down,
Insert_Door, Insert_Windows, Set_Roof_Trusses,
Install_Roof_Panels, General, General2 /
j 'unique skills' / Operate_Heavy_Equip, Mapping, Concrete_Fam,
3D_Printer_Software, Printer_Operations,
Concrete_Finishing, Structural_Wood_Working, Roofing,
Printer_Monitor_Op, Nozle_Op, General /
i 'AFSCs' / Electrician1, Electrician2, Electrician3,
PowerPro1, PowerPro2, PowerPro3,
HVAC1, HVAC2, HVAC3,
Horizontal1, Horizontal2, Horizontal3,
Structures1, Structures2, Structures3,
WFSM1, WFSM2, WFSM3,
EAs1, EAs2, EAs3,
Ops1, Ops2, Ops3 / ;

Parameters
r(n,j,t) binary for task n requiring skill j at time interval t
s(i,j) AFSC i has skill j
c(i,n) Cost associated with AFSC i completing task n
z(i) Cost associated with AFSC i being on the team
/ Electrician1 26026
Electrician2 26026
Electrician3 26026
PowerPro1 14300
PowerPro2 14300
PowerPro3 14300
HVAC1 26598
HVAC2 26598
HVAC3 26598
Horizontal1 21106
Horizontal2 21106
Horizontal3 21106
Structures1 25740
Structures2 25740
```

```
Structures3 25740
WFSM1 20592
WFSM2 20592
WFSM3 20592
EAs1 20460
EAs2 20460
EAs3 20460
Ops1 8294
Ops2 8294
Ops3 8294 /;

Scalars u,l;
u = 26;
l = 2;

Variables
x(i,n,t) AFSC i on n task at t time intervals
f Objective funciton value ;

Integer Variable x ;
*Positive Variable x ;

*these equations are both my constraints and optimization equation
Equations
* positiveint x is a set of + integer values for all i,n,t
upper(t) satisfy maximum number of team members
lower(t) satisfy minimum number of team members
taskpertime(i,t) one task for any time interval
skills(n,t) meet skill requirements for all tasks
obj minimizing the objective function ;

upper(t) .. sum((i,n), x(i,n,t)) =l= u ;

lower(t) .. sum((i,n), x(i,n,t)) =g= l ;

taskpertime(i,t).. sum(n, x(i,n,t)) =l= 1 ;

skills(n,t).. sum(i, x(i,n,t)) =e= sum(j,r(n,j,t)) ;

*obj .. f=e= sum((i,n,t), c(i,n)*x(i,n,t))+sum((i), max(x(i,n,t)*z(i))) ;
obj .. f=e= sum((i,n,t), c(i,n)*x(i,n,t))+sum((i,n,t), x(i,n,t)*z(i)) ;

*Minimize the number of personnel and minimize the number of AFSCs
*cost of that AFSC performing that task at that time + Cost of x number of AFSCs
*I want a model for personnel UTC using all of the definitions above
```

```
Model PersonnelUTC /all/ ;

*Bring in data here!
$onEcho > data_read_file.txt
i="C:\Users\GEM Student\OneDrive\Desktop\Dann Work\Tasks and Skills Table 3 per AFSC
Update Skills.xlsx"
r1=b228:b251
o1=set_i.inc

r2=c200:m200
o2=set_j.inc

r3=c172:q172
o3=set_n.inc

r4=e2:l2
o4=set_t.inc

r5=b172:q196
o5=pard_cin.inc

r6=b200:m224
o6=pard_sij.inc
$offEcho

$call =xls2gms @data_read_file.txt

$onEcho > rnjt.txt
I="C:\Users\GEM Student\OneDrive\Desktop\Dann Work\Tasks and Skills Table 3 per AFSC
Update Skills.xlsx"
R=B2:I168
O=rnjt.inc
$offEcho

$call =xls2gms @rnjt.txt

Table r(n,j,t) 'task n requiring skill j at time interval t'
$include rnjt.inc
;

$onEcho > sij.txt
I="C:\Users\GEM Student\OneDrive\Desktop\Dann Work\Tasks and Skills Table 3 per AFSC
Update Skills.xlsx"
R=b200:m224
O=sij.inc
```

```
$offEcho

$call =xls2gms @sij.txt

Table s(i,j)
$include sij.inc
;

$onEcho > cin.txt
I="C:\Users\GEM Student\OneDrive\Desktop\Dann Work\Tasks and Skills Table 3 per AFSC
Update Skills.xlsx"
R=b172:q196
O=cin.inc
$offEcho

$call =xls2gms @cin.txt

Table c(i,n)
$include cin.inc
;

Display r,s,c;

*solve the personnel utc optimization by minimizing the objective function
Solve PersonnelUTC using mip minimizing f ;

*disply the decision variables and the optimized solution
Display x.l, f.l ;
```

Model Parameters

Task n Requiring Skill j at Time t

Task (n)		Skill (j)	1	2	3	4	5	6	7	8
Map_Site	.	Operate_Heavy_Equip	0	0	0	0	0	0	0	0
Map_Site	.	Mapping	1	0	0	0	0	0	0	0
Map_Site	.	Concrete_Fam	0	0	0	0	0	0	0	0
Map_Site	.	3D_Printer_Software	0	0	0	0	0	0	0	0
Map_Site	.	Printer_Operations	0	0	0	0	0	0	0	0
Map_Site	.	Concrete_Finishing	0	0	0	0	0	0	0	0
Map_Site	.	Structural_Wood_Working	0	0	0	0	0	0	0	0
Map_Site	.	Roofing	0	0	0	0	0	0	0	0
Map_Site	.	Printer_Monitor_Op	0	0	0	0	0	0	0	0
Map_Site	.	Nozle_Op	0	0	0	0	0	0	0	0
Map_Site	.	General	0	0	0	0	0	0	0	0
Grade_Site	.	Operate_Heavy_Equip	0	1	0	0	0	0	0	0
Grade_Site	.	Mapping	0	0	0	0	0	0	0	0
Grade_Site	.	Concrete_Fam	0	0	0	0	0	0	0	0
Grade_Site	.	3D_Printer_Software	0	0	0	0	0	0	0	0
Grade_Site	.	Printer_Operations	0	0	0	0	0	0	0	0
Grade_Site	.	Concrete_Finishing	0	0	0	0	0	0	0	0
Grade_Site	.	Structural_Wood_Working	0	0	0	0	0	0	0	0
Grade_Site	.	Roofing	0	0	0	0	0	0	0	0
Grade_Site	.	Printer_Monitor_Op	0	0	0	0	0	0	0	0
Grade_Site	.	Nozle_Op	0	0	0	0	0	0	0	0
Grade_Site	.	General	0	0	0	0	0	0	0	0
Printer_Setup	.	Operate_Heavy_Equip	0	0	1	0	0	0	0	0
Printer_Setup	.	Mapping	0	0	0	0	0	0	0	0
Printer_Setup	.	Concrete_Fam	0	0	0	0	0	0	0	0
Printer_Setup	.	3D_Printer_Software	0	0	1	0	0	0	0	0
Printer_Setup	.	Printer_Operations	0	0	1	0	0	0	0	0
Printer_Setup	.	Concrete_Finishing	0	0	0	0	0	0	0	0
Printer_Setup	.	Structural_Wood_Working	0	0	0	0	0	0	0	0

Printer_Setup	.	Roofing	0	0	0	0	0	0	0	0
Printer_Setup	.	Printer_Monitor_Op	0	0	0	0	0	0	0	0
Printer_Setup	.	Nozle_Op	0	0	0	0	0	0	0	0
Printer_Setup	.	General	0	0	0	0	0	0	0	0
Mix_Concrete	.	Operate_Heavy_Equip	0	0	0	0	0	0	0	0
Mix_Concrete	.	Mapping	0	0	0	0	0	0	0	0
Mix_Concrete	.	Concrete_Fam	0	0	0	1	1	0	0	0
Mix_Concrete	.	3D_Printer_Software	0	0	0	0	0	0	0	0
Mix_Concrete	.	Printer_Operations	0	0	0	0	0	0	0	0
Mix_Concrete	.	Concrete_Finishing	0	0	0	0	0	0	0	0
Mix_Concrete	.	Structural_Wood_Working	0	0	0	0	0	0	0	0
Mix_Concrete	.	Roofing	0	0	0	0	0	0	0	0
Mix_Concrete	.	Printer_Monitor_Op	0	0	0	0	0	0	0	0
Mix_Concrete	.	Nozle_Op	0	0	0	0	0	0	0	0
Mix_Concrete	.	General	0	0	0	0	0	0	0	0
Feed_Pump_System	.	Operate_Heavy_Equip	0	0	0	0	0	0	0	0
Feed_Pump_System	.	Mapping	0	0	0	0	0	0	0	0
Feed_Pump_System	.	Concrete_Fam	0	0	0	1	1	0	0	0
Feed_Pump_System	.	3D_Printer_Software	0	0	0	0	0	0	0	0
Feed_Pump_System	.	Printer_Operations	0	0	0	0	0	0	0	0
Feed_Pump_System	.	Concrete_Finishing	0	0	0	0	0	0	0	0
Feed_Pump_System	.	Structural_Wood_Working	0	0	0	0	0	0	0	0
Feed_Pump_System	.	Roofing	0	0	0	0	0	0	0	0
Feed_Pump_System	.	Printer_Monitor_Op	0	0	0	0	0	0	0	0
Feed_Pump_System	.	Nozle_Op	0	0	0	0	0	0	0	0
Feed_Pump_System	.	General	0	0	0	0	0	0	0	0
Print_Foundation	.	Operate_Heavy_Equip	0	0	0	0	0	0	0	0
Print_Foundation	.	Mapping	0	0	0	0	0	0	0	0
Print_Foundation	.	Concrete_Fam	0	0	0	0	0	0	0	0
Print_Foundation	.	3D_Printer_Software	0	0	0	0	0	0	0	0
Print_Foundation	.	Printer_Operations	0	0	0	0	0	0	0	0
Print_Foundation	.	Concrete_Finishing	0	0	0	1	0	0	0	0
Print_Foundation	.	Structural_Wood_Working	0	0	0	0	0	0	0	0

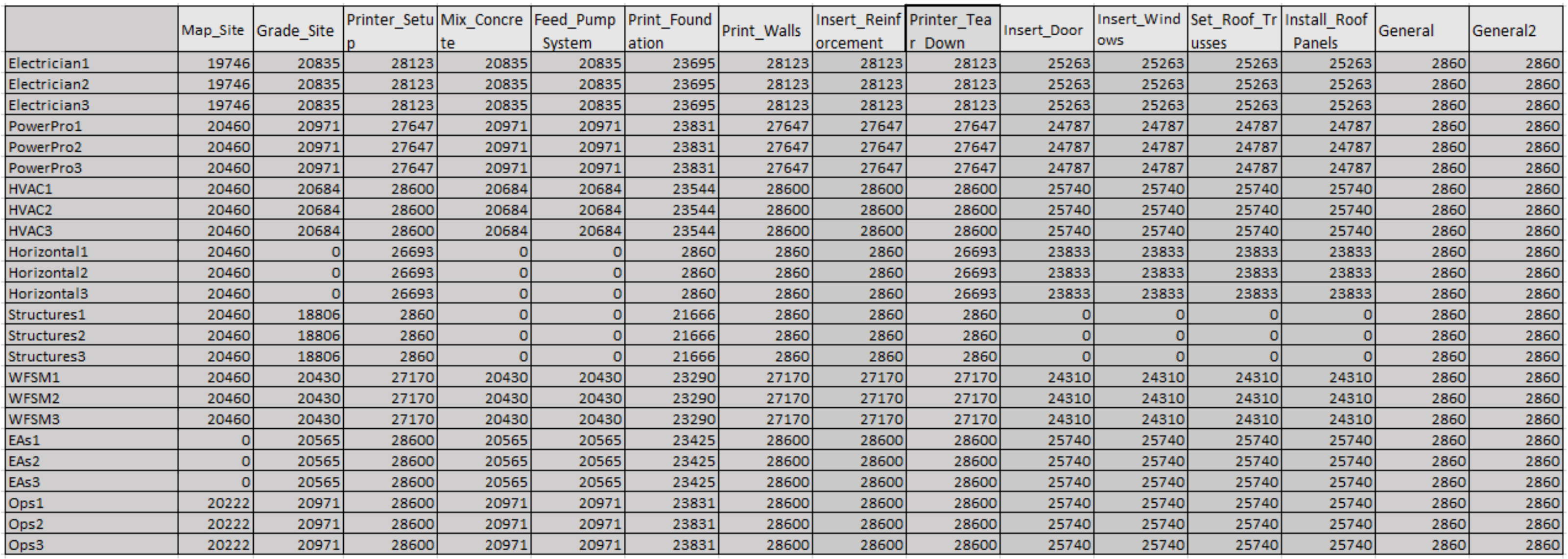
Print_Foundation	.	Roofing	0	0	0	0	0	0	0	0
Print_Foundation	.	Printer_Monitor_Op	0	0	0	1	0	0	0	0
Print_Foundation	.	Nozle_Op	0	0	0	1	0	0	0	0
Print_Foundation	.	General	0	0	0	0	0	0	0	0
Print_Walls	.	Operate_Heavy_Equip	0	0	0	0	0	0	0	0
Print_Walls	.	Mapping	0	0	0	0	0	0	0	0
Print_Walls	.	Concrete_Fam	0	0	0	0	0	0	0	0
Print_Walls	.	3D_Printer_Software	0	0	0	0	0	0	0	0
Print_Walls	.	Printer_Operations	0	0	0	0	0	0	0	0
Print_Walls	.	Concrete_Finishing	0	0	0	0	0	0	0	0
Print_Walls	.	Structural_Wood_Working	0	0	0	0	0	0	0	0
Print_Walls	.	Roofing	0	0	0	0	0	0	0	0
Print_Walls	.	Printer_Monitor_Op	0	0	0	0	1	0	0	0
Print_Walls	.	Nozle_Op	0	0	0	0	1	0	0	0
Print_Walls	.	General	0	0	0	0	0	0	0	0
Insert_Reinforcement	.	Operate_Heavy_Equip	0	0	0	0	0	0	0	0
Insert_Reinforcement	.	Mapping	0	0	0	0	0	0	0	0
Insert_Reinforcement	.	Concrete_Fam	0	0	0	1	1	0	0	0
Insert_Reinforcement	.	3D_Printer_Software	0	0	0	0	0	0	0	0
Insert_Reinforcement	.	Printer_Operations	0	0	0	0	0	0	0	0
Insert_Reinforcement	.	Concrete_Finishing	0	0	0	0	0	0	0	0
Insert_Reinforcement	.	Structural_Wood_Working	0	0	0	0	0	0	0	0
Insert_Reinforcement	.	Roofing	0	0	0	0	0	0	0	0
Insert_Reinforcement	.	Printer_Monitor_Op	0	0	0	0	0	0	0	0
Insert_Reinforcement	.	Nozle_Op	0	0	0	0	0	0	0	0
Insert_Reinforcement	.	General	0	0	0	0	0	0	0	0
Printer_Tear_Down	.	Operate_Heavy_Equip	0	0	0	0	0	1	0	0
Printer_Tear_Down	.	Mapping	0	0	0	0	0	0	0	0
Printer_Tear_Down	.	Concrete_Fam	0	0	0	0	0	0	0	0
Printer_Tear_Down	.	3D_Printer_Software	0	0	0	0	0	1	0	0
Printer_Tear_Down	.	Printer_Operations	0	0	0	0	0	1	0	0
Printer_Tear_Down	.	Concrete_Finishing	0	0	0	0	0	0	0	0
Printer_Tear_Down	.	Structural_Wood_Working	0	0	0	0	0	0	0	0

Printer_Tear_Down	.	Roofing	0	0	0	0	0	0	0	0
Printer_Tear_Down	.	Printer_Monitor_Op	0	0	0	0	0	0	0	0
Printer_Tear_Down	.	Nozle_Op	0	0	0	0	0	0	0	0
Printer_Tear_Down	.	General	0	0	0	0	0	0	0	0
Insert_Door	.	Operate_Heavy_Equip	0	0	0	0	0	0	0	0
Insert_Door	.	Mapping	0	0	0	0	0	0	0	0
Insert_Door	.	Concrete_Fam	0	0	0	0	0	0	0	0
Insert_Door	.	3D_Printer_Software	0	0	0	0	0	0	0	0
Insert_Door	.	Printer_Operations	0	0	0	0	0	0	0	0
Insert_Door	.	Concrete_Finishing	0	0	0	0	0	0	0	0
Insert_Door	.	Structural_Wood_Working	0	0	0	0	0	0	1	0
Insert_Door	.	Roofing	0	0	0	0	0	0	0	0
Insert_Door	.	Printer_Monitor_Op	0	0	0	0	0	0	0	0
Insert_Door	.	Nozle_Op	0	0	0	0	0	0	0	0
Insert_Door	.	General	0	0	0	0	0	0	0	0
Insert_Windows	.	Operate_Heavy_Equip	0	0	0	0	0	0	0	0
Insert_Windows	.	Mapping	0	0	0	0	0	0	0	0
Insert_Windows	.	Concrete_Fam	0	0	0	0	0	0	0	0
Insert_Windows	.	3D_Printer_Software	0	0	0	0	0	0	0	0
Insert_Windows	.	Printer_Operations	0	0	0	0	0	0	0	0
Insert_Windows	.	Concrete_Finishing	0	0	0	0	0	0	0	0
Insert_Windows	.	Structural_Wood_Working	0	0	0	0	0	0	1	0
Insert_Windows	.	Roofing	0	0	0	0	0	0	0	0
Insert_Windows	.	Printer_Monitor_Op	0	0	0	0	0	0	0	0
Insert_Windows	.	Nozle_Op	0	0	0	0	0	0	0	0
Insert_Windows	.	General	0	0	0	0	0	0	0	0
Set_Roof_Trusses	.	Operate_Heavy_Equip	0	0	0	0	0	0	1	0
Set_Roof_Trusses	.	Mapping	0	0	0	0	0	0	0	0
Set_Roof_Trusses	.	Concrete_Fam	0	0	0	0	0	0	0	0
Set_Roof_Trusses	.	3D_Printer_Software	0	0	0	0	0	0	0	0
Set_Roof_Trusses	.	Printer_Operations	0	0	0	0	0	0	0	0
Set_Roof_Trusses	.	Concrete_Finishing	0	0	0	0	0	0	0	0
Set_Roof_Trusses	.	Structural_Wood_Working	0	0	0	0	0	0	1	0

Set_Roof_Trusses	.	Roofing	0	0	0	0	0	0	1	0
Set_Roof_Trusses	.	Printer_Monitor_Op	0	0	0	0	0	0	0	0
Set_Roof_Trusses	.	Nozle_Op	0	0	0	0	0	0	0	0
Set_Roof_Trusses	.	General	0	0	0	0	0	0	0	0
Install_Roof_Panels	.	Operate_Heavy_Equip	0	0	0	0	0	0	0	0
Install_Roof_Panels	.	Mapping	0	0	0	0	0	0	0	0
Install_Roof_Panels	.	Concrete_Fam	0	0	0	0	0	0	0	0
Install_Roof_Panels	.	3D_Printer_Software	0	0	0	0	0	0	0	0
Install_Roof_Panels	.	Printer_Operations	0	0	0	0	0	0	0	0
Install_Roof_Panels	.	Concrete_Finishing	0	0	0	0	0	0	0	0
Install_Roof_Panels	.	Structural_Wood_Working	0	0	0	0	0	0	0	1
Install_Roof_Panels	.	Roofing	0	0	0	0	0	0	0	1
Install_Roof_Panels	.	Printer_Monitor_Op	0	0	0	0	0	0	0	0
Install_Roof_Panels	.	Nozle_Op	0	0	0	0	0	0	0	0
Install_Roof_Panels	.	General	0	0	0	0	0	0	0	0
General	.	Operate_Heavy_Equip	0	0	0	0	0	0	0	0
General	.	Mapping	0	0	0	0	0	0	0	0
General	.	Concrete_Fam	0	0	0	0	0	0	0	0
General	.	3D_Printer_Software	0	0	0	0	0	0	0	0
General	.	Printer_Operations	0	0	0	0	0	0	0	0
General	.	Concrete_Finishing	0	0	0	0	0	0	0	0
General	.	Structural_Wood_Working	0	0	0	0	0	0	0	0
General	.	Roofing	0	0	0	0	0	0	0	0
General	.	Printer_Monitor_Op	0	0	0	0	0	0	0	0
General	.	Nozle_Op	0	0	0	0	0	0	0	0
General	.	General	1	1	1	1	1	1	1	1
General2	.	Operate_Heavy_Equip	0	0	0	0	0	0	0	0
General2	.	Mapping	0	0	0	0	0	0	0	0
General2	.	Concrete_Fam	0	0	0	0	0	0	0	0
General2	.	3D_Printer_Software	0	0	0	0	0	0	0	0
General2	.	Printer_Operations	0	0	0	0	0	0	0	0
General2	.	Concrete_Finishing	0	0	0	0	0	0	0	0
General2	.	Structural_Wood_Working	0	0	0	0	0	0	0	0

General2	.	Roofing	0	0	0	0	0	0	0	0
General2	.	Printer_Monitor_Op	0	0	0	0	0	0	0	0
General2	.	Nozle_Op	0	0	0	0	0	0	0	0
General2	.	General	1	1	1	1	1	1	1	1

Cost of AFSC (i) Completing Task (n)



	Map_Site	Grade_Site	Printer_Setup	Mix_Concrete	Feed_Pump System	Print_Foundation	Print_Walls	Insert_Reinforcement	Printer_Tear Down	Insert_Door	Insert_Windows	Set_Roof_Trusses	Install_Roof Panels	General	General2
Electrician1	19746	20835	28123	20835	20835	23695	28123	28123	28123	25263	25263	25263	25263	2860	2860
Electrician2	19746	20835	28123	20835	20835	23695	28123	28123	28123	25263	25263	25263	25263	2860	2860
Electrician3	19746	20835	28123	20835	20835	23695	28123	28123	28123	25263	25263	25263	25263	2860	2860
PowerPro1	20460	20971	27647	20971	20971	23831	27647	27647	27647	24787	24787	24787	24787	2860	2860
PowerPro2	20460	20971	27647	20971	20971	23831	27647	27647	27647	24787	24787	24787	24787	2860	2860
PowerPro3	20460	20971	27647	20971	20971	23831	27647	27647	27647	24787	24787	24787	24787	2860	2860
HVAC1	20460	20684	28600	20684	20684	23544	28600	28600	28600	25740	25740	25740	25740	2860	2860
HVAC2	20460	20684	28600	20684	20684	23544	28600	28600	28600	25740	25740	25740	25740	2860	2860
HVAC3	20460	20684	28600	20684	20684	23544	28600	28600	28600	25740	25740	25740	25740	2860	2860
Horizontal1	20460	0	26693	0	0	2860	2860	2860	26693	23833	23833	23833	23833	2860	2860
Horizontal2	20460	0	26693	0	0	2860	2860	2860	26693	23833	23833	23833	23833	2860	2860
Horizontal3	20460	0	26693	0	0	2860	2860	2860	26693	23833	23833	23833	23833	2860	2860
Structures1	20460	18806	2860	0	0	21666	2860	2860	2860	0	0	0	0	2860	2860
Structures2	20460	18806	2860	0	0	21666	2860	2860	2860	0	0	0	0	2860	2860
Structures3	20460	18806	2860	0	0	21666	2860	2860	2860	0	0	0	0	2860	2860
WFSM1	20460	20430	27170	20430	20430	23290	27170	27170	27170	24310	24310	24310	24310	2860	2860
WFSM2	20460	20430	27170	20430	20430	23290	27170	27170	27170	24310	24310	24310	24310	2860	2860
WFSM3	20460	20430	27170	20430	20430	23290	27170	27170	27170	24310	24310	24310	24310	2860	2860
EAs1	0	20565	28600	20565	20565	23425	28600	28600	28600	25740	25740	25740	25740	2860	2860
EAs2	0	20565	28600	20565	20565	23425	28600	28600	28600	25740	25740	25740	25740	2860	2860
EAs3	0	20565	28600	20565	20565	23425	28600	28600	28600	25740	25740	25740	25740	2860	2860
Ops1	20222	20971	28600	20971	20971	23831	28600	28600	28600	25740	25740	25740	25740	2860	2860
Ops2	20222	20971	28600	20971	20971	23831	28600	28600	28600	25740	25740	25740	25740	2860	2860
Ops3	20222	20971	28600	20971	20971	23831	28600	28600	28600	25740	25740	25740	25740	2860	2860

2 Per AFSC Model Output

Final Solution	=	957574.79	10 positions

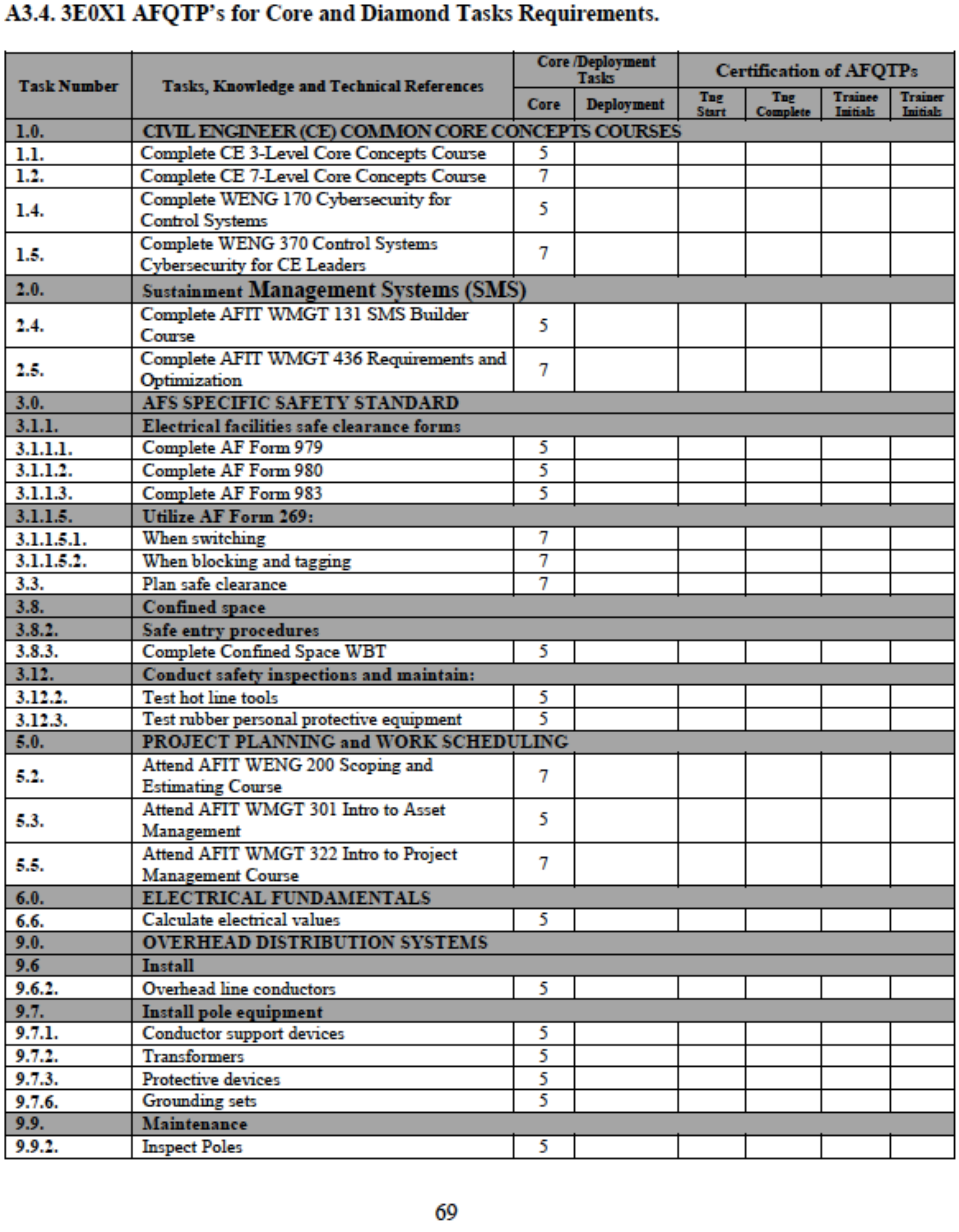
			1	2	3	4	5	6	7	8
			1	1	2	24	24	2	4	8
PowerPro1	.	Printer_Setup			1					
PowerPro1	.	Print_Foundation				1				
PowerPro1	.	Printer_Tear_Down						1		
PowerPro1	.	Set_Roof_Trusses							1	
PowerPro2	.	Set_Roof_Trusses							1	
PowerPro2	.	General				1	1			
Horizontal1	.	Grade_Site		1						
Horizontal1	.	Print_Foundation				1				
Horizontal1	.	Print_Walls					1			
Horizontal2	.	Print_Walls					1			
Horizontal2	.	Insert_Reinforcement				1				
Structures1	.	Printer_Setup			1					
Structures1	.	Feed_Pump_System				1				
Structures1	.	Insert_Reinforcement					1			
Structures1	.	Printer_Tear_Down						1		
Structures1	.	Insert_Door							1	
Structures1	.	Install_Roof_Panels								1
Structures2	.	Printer_Setup			1					
Structures2	.	Mix_Concrete				1	1			
Structures2	.	Printer_Tear_Down						1		
Structures2	.	Set_Roof_Trusses							1	
Structures2	.	Install_Roof_Panels								1
WFSM1	.	Insert_Windows							1	
EAs1	.	Map_Site	1							
Ops1	.	Print_Foundation				1				
Ops1	.	General2	1	1	1		1	1	1	1
Ops2	.	Feed_Pump_System					1			
Ops2	.	General	1	1	1			1	1	1
Ops2	.	General2				1				

4FPET Team Composition AFSC Model Output

Final Solution	=	899292.67	12 positions
Non utilized positions		307318	13/25 positions not used
Total		1206610.67	

			1	2	3	4	5	6	7	8
PowerPro1	.	Insert_Windows							1	
PowerPro2	.	General2	1	1	1	1	1	1	1	1
Horizontal1	.	Grade_Site		1						
Horizontal1	.	Print_Foundation				1				
Horizontal1	.	Print_Walls					1			
Horizontal2	.	Print_Foundation				1				
Horizontal2	.	Print_Walls					1			
Horizontal3	.	Print_Foundation				1				
Horizontal3	.	Insert_Reinforcement					1			
Horizontal4	.	Mix_Concrete				1	1			
Structures1	.	Printer_Setup			1					
Structures1	.	Printer_Tear_Down						1		
Structures1	.	Set_Roof_Trusses							1	
Structures1	.	Install_Roof_Panels								1
Structures2	.	Printer_Setup			1					
Structures2	.	Feed_Pump_System					1			
Structures2	.	Insert_Reinforcement				1				
Structures2	.	Printer_Tear_Down						1		
Structures2	.	Set_Roof_Trusses							1	
Structures2	.	Install_Roof_Panels								1
Structures3	.	Printer_Setup			1					
Structures3	.	Feed_Pump_System				1				
Structures3	.	Printer_Tear_Down						1		
Structures3	.	Set_Roof_Trusses							1	
Structures4	.	Insert_Door							1	
EAs1	.	Map_Site	1							
Ops1	.	General	1	1	1	1	1	1	1	1

3E0X1 Core and Diamond Skills Table Excerpt



A3.4. 3E0X1 AFQTP's for Core and Diamond Tasks Requirements.

Task Number	Tasks, Knowledge and Technical References	Core /Deployment Tasks		Certification of AFQTPs			
		Core	Deployment	Tng Start	Tng Complete	Trainee Initials	Trainer Initials
1.0.	**CIVIL ENGINEER (CE) COMMON CORE CONCEPTS COURSES**						
1.1.	Complete CE 3-Level Core Concepts Course	5					
1.2.	Complete CE 7-Level Core Concepts Course	7					
1.4.	Complete WENG 170 Cybersecurity for Control Systems	5					
1.5.	Complete WENG 370 Control Systems Cybersecurity for CE Leaders	7					
2.0.	**Sustainment Management Systems (SMS)**						
2.4.	Complete AFIT WMGT 131 SMS Builder Course	5					
2.5.	Complete AFIT WMGT 436 Requirements and Optimization	7					
3.0.	**AFS SPECIFIC SAFETY STANDARD**						
3.1.1.	**Electrical facilities safe clearance forms**						
3.1.1.1.	Complete AF Form 979	5					
3.1.1.2.	Complete AF Form 980	5					
3.1.1.3.	Complete AF Form 983	5					
3.1.1.5.	**Utilize AF Form 269:**						
3.1.1.5.1.	When switching	7					
3.1.1.5.2.	When blocking and tagging	7					
3.3.	Plan safe clearance	7					
3.8.	**Confined space**						
3.8.2.	**Safe entry procedures**						
3.8.3.	Complete Confined Space WBT	5					
3.12.	**Conduct safety inspections and maintain:**						
3.12.2.	Test hot line tools	5					
3.12.3.	Test rubber personal protective equipment	5					
5.0.	**PROJECT PLANNING and WORK SCHEDULING**						
5.2.	Attend AFIT WENG 200 Scoping and Estimating Course	7					
5.3.	Attend AFIT WMGT 301 Intro to Asset Management	5					
5.5.	Attend AFIT WMGT 322 Intro to Project Management Course	7					
6.0.	**ELECTRICAL FUNDAMENTALS**						
6.6.	Calculate electrical values	5					
9.0.	**OVERHEAD DISTRIBUTION SYSTEMS**						
9.6	**Install**						
9.6.2.	Overhead line conductors	5					
9.7.	**Install pole equipment**						
9.7.1.	Conductor support devices	5					
9.7.2.	Transformers	5					
9.7.3.	Protective devices	5					
9.7.6.	Grounding sets	5					
9.9.	**Maintenance**						
9.9.2.	Inspect Poles	5					

Appendix B

Instructions on Updating the Team Selection Model

Background:
GAMS uses the function XLS2GMS to call information from data tables built in excel. Edits made in the called excel files will automatically be pulled into this code once saved. The body of the code will also have to be updated so that the correct cells are being drawn from excel. Additionally, the input AFSC composition will also have to be updated so that the correct personnel are being considered. GAMS is a fairly user friendly language that will tell you where your code is having issues but the big thing is to make sure everything matches. If you update your excel WBS and r(n,j,t) parameter make sure your set reflects those changes in GAMS.

Step 1: Assuming that this is being used for any type of project the first thing that will need be updated is the project work breakdown structure. This will define the time periods, primary tasks and drive towards the skills required.

Step 2: With the tasks established the user can go through each task and determine what skills are required for each of those tasks.

Step 3: With the tasks, skills and time periods required the r(n,j,t) parameter can be built. This is one of the primary parameters this code uses in this model. The user will build the parameter similar to the one provided in Appendix A: Task n Requiring Skill j at Time t. A binary system is used to establish that if a task requires a skill and in what time that task skill requirement must be performed. Once this table has been updated for said project the parameter is complete and the code inside GAMS must be updated to ensure the correct cells are being pulled into GAMS.

Step 4: NOT REQUIRED: At some point in time when/if the cost parameter has become more established the costs for an AFSC to have the skills to perform other AFSC tasks can be updated in the c(i,n) table, an example of this table is included in Appendix A: Cost of AFSC (i) Completing Task (n). The current cost table can continue to be used it only needs to be updated if the input AFSC options change.

Step 5: Ensure that you are inputting the correct AFSC team options into the z(i) cost of being on the team parameter.

Step 6: Update each of the sets t, n, j and i based on the current WBS and team being tested.

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Dann, Caleb G
Moore, Brigham A

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Institute of Technology
Graduate School of Engineering and Management (AFIT/EN)
2950 Hobson Way, Building 640
WPAFB, OH 45433-7765

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Air Force Civil Engineer Center
Charles Nikon
2261 Hughes Ave, Ste.155.
JBSA Lackland, TX 78236-9853

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14. ABSTRACT
Additive Manufacturing Construction (AMC) is an emerging technology in the construction industry which utilizes 3-D printing to reduce costs, labor requirements and deviations in quality. This technology has the ability to rapidly produce repeatable construction projects while tailoring each to specific requirements through the use of 3-D designs. One of the primary objectives of the 2018 National Defense Strategy (NDS) is to continue meeting mission demands with a greater focus on the efficient use of resources. AMC has the ability to satisfy the requirements of this objective. The United States Air Force has begun initial print trials but have not yet fully operationalized this technology. This study implements several decision-making methodologies which provide leaders with a framework for implementing this technology in terms of personnel training, team composition, and equipment selection. The outcome of this work is the identification of an optimized team composition capable of performing AMC based on their current skills and potential future skills along with a methodology to select the equipment that best fits the expeditionary construction needs of the Air Force.

15. SUBJECT TERMS
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Multi-Attribute Utility Theory (MAUT)
Unit Type Code (UTC)

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