2021-06

NAVY EXPEDITIONARY ADDITIVE MANUFACTURING (NEAM) CAPABILITY INTEGRATION

Amodeo, Leslie J.; Dick, Brian B.; Flynn, Charles P.; Nagurney, Rebecca A.; Parker, Meagan B.

Monterey, CA; Naval Postgraduate School

http://hdl.handle.net/10945/67651

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

SYSTEMS ENGINEERING CAPSTONE REPORT

NAVY EXPEDITIONARY ADDITIVE MANUFACTURING (NEAM) CAPABILITY INTEGRATION

by

Leslie J. Amodeo, Brian B. Dick, Charles P. Flynn,
Rebecca A. Nagurney, and Meagan B. Parker

June 2021

Advisor:	Douglas L. Van Bossuyt
Co-Advisor:	Amela Sadagic

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** June 2021	**3. REPORT TYPE AND DATES COVERED** Systems Engineering Capstone Report

4. TITLE AND SUBTITLE NAVY EXPEDITIONARY ADDITIVE MANUFACTURING (NEAM) CAPABILITY INTEGRATION	**5. FUNDING NUMBERS**
6. AUTHOR(S) Leslie J. Amodeo, Brian B. Dick, Charles P. Flynn, Rebecca A. Nagurney, and Meagan B. Parker	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.	**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

This capstone report analyzes the current and future use of additive manufacturing (AM) technologies within the Department of Defense (DOD). This analysis provided the technical background necessary to develop the Additive Manufacturing Process and Analysis Tool (AMPAT). AMPAT will help stakeholders identify what AM equipment best serves warfighters and their missions in expeditionary environments. Furthermore, the tool can be used by stakeholders to identify the most advantageous dispersions of AM capabilities across the fleet and make decisions on how those capabilities should be integrated into the greater naval mission and larger DOD enterprise. A systems engineering (SE) approach was implemented to gather information on current and prospective AM methods in order to understand and define the AM system operational requirements. Additionally, an SE process was utilized to analyze alternative software options to build the tool, implement agile software development processes to develop the tool, and verify and validate that the tool met the project requirements. The study found that AMPAT successfully outputs a ranked list of AM systems recommendations based upon user-defined input parameters and weighting values. Recommendations for choosing AM equipment and developing dispersion plans for the fleet include using the AMPAT deliverable to conduct customized, iterative analysis with user-defined inputs that are tailored to specific expeditionary environments.

14. SUBJECT TERMS additive manufacturing, expeditionary warfare, systems engineering, 3D printers, Navy Expeditionary Combat Command	**15. NUMBER OF PAGES** 141
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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Leslie J. Amodeo, Brian B. Dick, Charles P. Flynn,
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Submitted in partial fulfillment of the
requirements for the degrees of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

and

MASTER OF SCIENCE IN ENGINEERING SYSTEMS

from the

NAVAL POSTGRADUATE SCHOOL
June 2021

Lead Editor: Meagan B. Parker

Reviewed by:	
Douglas L. Van Bossuyt	Amela Sadagic
Advisor	Co-Advisor

Accepted by:
Ronald E. Giachetti
Chair, Department of Systems Engineering

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ABSTRACT

This capstone report analyzes the current and future use of additive manufacturing (AM) technologies within the Department of Defense (DOD). This analysis provided the technical background necessary to develop the Additive Manufacturing Process and Analysis Tool (AMPAT). AMPAT will help stakeholders identify what AM equipment best serves warfighters and their missions in expeditionary environments. Furthermore, the tool can be used by stakeholders to identify the most advantageous dispersions of AM capabilities across the fleet and make decisions on how those capabilities should be integrated into the greater naval mission and larger DOD enterprise. A systems engineering (SE) approach was implemented to gather information on current and prospective AM methods in order to understand and define the AM system operational requirements. Additionally, an SE process was utilized to analyze alternative software options to build the tool, implement agile software development processes to develop the tool, and verify and validate that the tool met the project requirements. The study found that AMPAT successfully outputs a ranked list of AM systems recommendations based upon user-defined input parameters and weighting values. Recommendations for choosing AM equipment and developing dispersion plans for the fleet include using the AMPAT deliverable to conduct customized, iterative analysis with user-defined inputs that are tailored to specific expeditionary environments.

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LIST OF ACRONYMS AND ABBREVIATIONS

ABS	acrylonitrile butadiene styrene
AM	additive manufacturing
AML	additive manufacturing laboratory
AMOC	Advanced Manufacturing Operations Cell
AMPAT	Additive Manufacturing Process and Analysis Tool
ANB	advanced naval base
CAD	computer aided design
CNC	computer numerical control
CONUS	Continental United States
COTS	commercial off-the-shelf
CUI	controlled unclassified information
DAU	Defense Acquisition University
DED	directed energy deposition
DIU	Defense Innovation Unit
DMO	distributed maritime operations
DOD	Department of Defense
DODAF	Department of Defense Architecture Framework
DON	Department of the Navy
EAB	expeditionary advanced bases
EABO	expeditionary advanced base operations
EBM	electron beam melting
EX Lab	Expeditionary Lab
EXMAN	Expeditionary Manufacturing Mobile Test Bed
FDM	fused deposition modeling
FEA	finite element analysis
FFF	fused filament fabrication
FOB	forward operating base
FRP	fiber reinforced plastic

GUI	graphical user interface
HMMWV	high mobility multipurpose wheeled vehicle
HSI	human systems integration
LOCE	littoral operations in a contested environment
MCSC	Marine Corps Systems Command
MDT	mean downtime
MSRP	manufacturer suggested retail price
MTBF	mean time between failure
MVP	minimum viable product
NAM EXCOMM	Naval Additive Manufacturing Executive Committee
NAVFAC	Naval Facilities Engineering Systems Command
NAVSUP	Naval Supply Systems Command
NEAM	Naval Expeditionary Additive Manufacturing
NECC	Navy Expeditionary Combat Command
NPS	Naval Postgraduate School
OCONUS	outside the Continental United States
ONR	Office of Naval Research
PEO	Program Executive Office
PLA	polylactic acid
POC	point of contact
PPE	personal protective equipment
REF	Rapid Equipping Force
RVTM	requirements verification and validation test matrix
SEMS	Shop Equipment, Machine Shop
SLA	stereolithography
SLM	selective laser melting
SLS	selective laser sintering
SME	subject matter expert
SOP	standard operating procedure
SPAWAR	Space and Naval Warfare Systems Command

UAV	unmanned aerial vehicle
USMC	United States Marine Corps
UV	ultraviolet
V&V	verification and validation
VBA	Visual Basic for Applications
X-FAB	Expeditionary Fabrication Facility

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EXECUTIVE SUMMARY

The Navy and Marine Corps have been increasing the use of additive manufacturing (AM) capabilities in various operational environments and mission scenarios to rapidly deliver warfighting equipment, reduce costs, and replace and repair components. The Naval Postgraduate School (NPS) Naval Expeditionary Additive Manufacturing (NEAM) team was established to address several research questions posed by the Navy Expeditionary Combat Command (NECC). The team developed a tool called the Additive Manufacturing Process and Analysis Tool (AMPAT) that will 1) identify specific AM equipment to best serve the force in expeditionary environments including distributed maritime operations (DMO), littoral operations in a contested environment (LOCE), and expeditionary advanced base operations (EABO), 2) output recommendations that can be used to help inform dispersion plans of AM equipment across the fleet, and 3) help the NECC better integrate their capabilities into the greater naval mission. The NEAM team used a modified Waterfall Process Model systems engineering approach to develop a tool to answer these questions.

The NEAM team conducted a detailed literature review to collect information on various AM technologies, design considerations for AM parts, material handling, and the use of AM in the DOD. Additionally, the team met with many subject matter experts (SMEs) from organizations that work with AM technologies including the Naval Facilities (NAVFAC) Engineering and Expeditionary Warfare Center, Naval Sea Systems Command Technology Office, Marine Corps Systems Command, Naval Surface Warfare Center Indian Head Division, Naval Surface Warfare Center Pt. Hueneme Division, 1st Marine Logistics Group, Marine Forces Command, Naval Supply Systems Command (NAVSUP), Naval Information Warfare Center Pacific, and the Office of Naval Research.

The AMPAT deliverable is an Excel-based tool written in the Visual Basic for Applications (VBA) programming language. The AMPAT includes a database for users to input information and data for various AM systems, as well as a tool dashboard that allows the user to easily navigate between required inputs to conduct the analysis and the outputs from the analysis. The dashboard allows users to exercise tool functions, including

adjusting the analysis criteria and user selections, adding a printer to the AM database, error checking the AM database, running the analysis, and clearing the results. Users can customize the AMPAT analysis to rank a set of AM printers with different specifications and characteristics to identify optimal AM system designs for warfighter needs in specific environments. Comprehensive, step-by-step instructions for how to use each function of the AMPAT can be found in the User's Guide.

This report provides a methodology for users to execute the AMPAT to obtain analysis results. First, the user sets the analysis parameters by identifying the specific attributes of interest (e.g., failure rate, operational availability, environmental conditions). Next, the user sets weighting values to each of the selected attributes to rank the importance of each attribute relative to one another. The user must set the weight values in order for the AMPAT to perform the mathematical analysis necessary to provide specific AM system recommendations. The mathematical analysis will compute and normalize the weighted scores of each AM system based upon the user weight inputs for each attribute. The AMPAT will generate a filtered database sheet that includes the AM systems that satisfy the input parameters identified by the user prior to running the analysis. Additionally, a ranked list of those AM systems will be provided based upon the weighting values that were assigned to each parameter. Lastly, the AMPAT will plot the results of the analysis; the user can choose specific parameters to include in the plot, as well as decide whether to plot by system or plot by attribute.

The NEAM team recommends that the NECC conduct iterative analysis with the AMPAT and continue to add new AM systems and system attributes to the database. As new information is input into the tool, users will receive more detailed results that may influence the final AM rankings. The rankings provided by the AMPAT will advise decision makers on which AM equipment would best serve the force in execution of DMO, LOCE, and EABO environments. Additionally, the NEAM team recommends that the NECC up-domain the AMPAT to an environment with the appropriate security classification to customize the analysis for the tool to provide recommendations for AM systems for specific locations in the fleet. Given the proper inputs, the results of this analysis could be used to determine the best strategy to preposition AM technologies throughout the fleet.

In order to unify the DON and the DOD, experts within the AM field must work together to develop a strategy document that establishes criteria necessary to approve AM systems for DOD use. The AMPAT should be used in tandem to assist the community in evaluating different AM technologies to determine suitability for DOD missions and operational scenarios. As the users continue to populate AMPAT with additional AM systems and iteratively conduct analysis with varying parameters, the results and outputs from the tool can be used to justify DOD approval decisions.

The NEAM team also recommends that the AMPAT should be expanded upon to include a library or repository of parts and part specifications. This would expand the utility of the AMPAT and allow it to make recommendations for AM systems that should be used to print specific parts to support ships, submarines, aircraft, and other vehicles or equipment. Ultimately, this would reduce costs and shorten schedules for the fleet to rapidly produce tailored parts to enhance warfighter readiness.

The AMPAT provides a decision analysis process to identify the most ideal AM equipment to support specific missions and heighten awareness of AM capabilities across the DOD. AM technologies play a crucial role in ensuring expeditious and methodical sustainment of warfighting equipment and enhancing fleet readiness. The use of the AMPAT will help align the DON and DOD to progress AM technology in a unified effort to support the needs of the greater naval mission.

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ACKNOWLEDGMENTS

The NEAM team would like to thank their advisors, Dr. Douglas Van Bossuyt and Dr. Amela Sadagic, for their guidance and support throughout the capstone process. Their expertise in the additive manufacturing industry and their dedication to ensuring the success of each student was tremendously motivating. Additionally, the team would like to thank all the organizations and subject matter experts that took time out of their very busy schedules to discuss additive manufacturing processes, policies, and technologies. The information gathered from those technical meetings significantly augmented the team's research and laid the foundation for tool development.

The NEAM team would also like to thank their respective commands for the opportunity to attend the NPS. Finally, the successful execution of this capstone project would not have been possible without the devotion of the team members' families. Their patience and support throughout the entirety of the NPS Systems Engineering master's program was deeply appreciated.

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I. INTRODUCTION

This chapter defines the problem statement, objectives, scope, and operational scenarios for this research project. Additionally, this chapter explains the methodology that was used to develop the tool and how the tool will be used by the primary stakeholder, the Navy Expeditionary Combat Command (NECC), and other stakeholders to satisfy the research objectives.

A. PROBLEM STATEMENT

For several years, the Navy and Marine Corps have been employing additive manufacturing (AM) capabilities in operational environments to rapidly deliver warfighting equipment. Research must be done to determine how to integrate future AM capabilities, while maximizing return on investment and minimizing duplicated efforts. The overarching goal is for this research to be applied to capabilities deployed in various environments such as: distributed maritime operations (DMO), littoral operations in contested environments (LOCE), and expeditionary advanced base operations (EABO). For the purposes of this report, the focus is on the development of a tool and database to assist decision makers when determining the appropriate AM to use within these environments.

Additive manufacturing has been proven to be extremely beneficial by providing reduced costs and fast component replacement and repair; the specific advantages and disadvantages of AM are discussed in more detail in the following sections of this report. Because AM is a rapidly advancing technology field, it is difficult to consistently compare and weigh technology capabilities and attributes to meet ever-changing needs. A tool is needed to provide leadership adequate insight into what capabilities the current and new AM technology provides, so they can make informed decisions to maximize the return on investment for the Department of Defense (DOD) in support of the warfighter and their missions. Some characteristics that need to be considered for decision makers include: mobility, ease of use, training, printing materials, and printer bed size.

The purpose of this project is to provide an overarching decision analysis method and tool that includes an easily modifiable database of current 3D printers and parts for the NECC, to efficiently integrate current and future AM capabilities into the broader Navy expeditionary mission. The Navy Expeditionary Additive Manufacturing (NEAM) team extensively researched current AM capabilities and their applications for expeditionary forces to help develop the analysis method, tool, and database that NECC can adopt and use to determine how to best disperse AM capabilities and maximize benefits across the U.S. Navy fleet. While there is a broad need and great potential for AM integration within the naval expeditionary forces, and broadly within the Navy and DOD, the NEAM project focused on AM as a supportability capability for deployed systems, platforms, and vehicles. Ultimately, this plan will serve as a reference and guide for the NECC, to make informed decisions with respect to AM equipment deployment strategies and acquisitions for the Navy and Marines.

B. RESEARCH OBJECTIVES AND PROJECT SCOPE

This project focused on how the NECC can maximize return on investment and minimize duplication of efforts when deploying AM equipment for use by expeditionary forces. This research feeds into the overall goal of deploying AM capabilities in DMO, LOCE, EABO, and other situations, while ensuring interoperability with existing efforts, minimizing duplicated efforts, and maximizing return on investment. In order not to duplicate work, the team leveraged previous work completed for similar efforts and coordinated with ongoing AM efforts within the Navy. The objective of this research is to provide the NECC with a decision analysis process that will guide decision makers in choosing the most effective AM technologies to fulfill specific use cases within expeditionary environments.

Each of the three aforementioned expeditionary environments (i.e., DMO, LOCE, and EABO) have their own unique needs for AM technology. The DMO environment concentrates the Navy on peer and near-peer competitors, which requires fleet level engagement in major combat operations. To do this, it posits more integrated relationships amongst commands and promotes calculated risk acceptance. Likewise, the *EABO*

Handbook states that, "EABO is a future naval operational concept that meets the resiliency and forward presence requirements of the next paradigm of U.S. Joint expeditionary operations" (Marine Corps Association 2018, 5). This strategy provides the opportunity to conduct expeditionary operations to defeat an adversary's strategy without destroying all enemy forces. Further, the *EABO Handbook* "encourages both the Marine Corps and Navy to develop optimized inside force capabilities to serve within the overall DMO construct" (Marine Corps Association 2018, 22). The LOCE concept describes naval operations in the littoral environment considering emerging threats to provide an innovative, joined framework for the Navy and Marine Corps (Littoral Operations in a Contested Environment, 2020). AM plays a critical role in ensuring that the warfighters are properly equipped within these environments.

In consideration of these environments, the NEAM project focused on the following questions to address critical gaps in warfighter capabilities using AM technologies:

1. What AM equipment would best serve the force in execution of DMO/ LOCE/EABO including the consideration of interoperability with other USMC and Navy forces?
2. What are the most advantageous dispersions of AM capabilities across the fleet to maximize benefits including potential prepositioning of equipment?
3. How can NECC better integrate their capabilities into the greater naval mission?

This project was not intended to analyze every portion of AM implementation; therefore, future work will build on the foundation of this project. Future work was also identified as a mitigating factor to reduce the risk of scope creep. The NEAM team recommendations for future work can be found in Chapter VII, Section A.

C. METHODOLOGY

To accomplish the project goals of assisting the NECC to maximize return on investment and minimize duplication, this research focused on developing a database and tool to assist in decision making and increasing exposure to available AM capabilities for specific missions and goals. The tool and database were developed using Microsoft Office products because of its typical availability on computer systems throughout the federal government. This will help to ensure it can be widely distributed and used by a large audience throughout the Navy.

The tool was developed using software selected during the systems engineering process. It focuses on various capabilities of AM systems as defined by the stakeholders and NECC. Users can load various characteristics of AM systems and assigned weights using the built-in graphical user interface (GUI). The tool outputs AM system recommendations based on the assigned weighting of the characteristics for the desired expeditionary environment.

To ensure the deliverable met stakeholder needs, the NEAM team used a systems engineering approach that included continuous feedback from the stakeholders, which is described in detail in Chapter IV. This allowed the stakeholders to provide input on the specific direction of the research as the project progressed and for the NEAM team to provide information and analysis results as it became available.

D. REPORT STRUCTURE

Chapter I of this report explains the problem statement, the objectives and scope of the research, and the approach used to develop the deliverables in this project. Chapter II includes an extensive and detailed description of the literature review the NEAM team conducted in order to collect information on different types of AM technology, how AM parts are designed, material handling considerations, and how AM is specifically used within the DOD. Additionally, Chapter II describes the systems engineering approach that the NEAM team used to complete the project, as well as alternative approaches that were considered. Chapter III focuses on stakeholder identification and analysis and describes the primary stakeholder needs, the process that was used to translate them into specific requirements, and the gaps that exist within current AM capabilities. Chapter IV provides an overview of the Additive Manufacturing Process and Analysis Tool (AMPAT) code development process and the software processes that were followed, as well as the capabilities and limitations of the tool. Chapter V provides several use cases for the AMPAT and describes the operational environments for which the tool is intended to be used. Chapter VI provides a comprehensive explanation for how AMPAT can be used to retrieve analysis results for a specific mission, as well as explains the verification and validation (V&V) methodology used to ensure the tool met project requirements and stakeholder needs. Chapter VII documents the conclusions drawn by the development team, summarizes the benefit of the research and analysis to the stakeholders and DOD, and provides recommendations for future work.

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II. LITERATURE REVIEW AND SYSTEMS ENGINEERING PROCESS

This chapter describes the literature that was reviewed by the NEAM team to collect information on AM technology and processes. The specific topics of interest for this literature review include: AM technology background, design considerations for AM parts, material handling, and use of AM in the DOD. Additionally, this chapter explains the systems engineering process the NEAM Team used to complete the project, as well as the alternative approaches that were considered.

A. ADDITIVE MANUFACTURING TECHNOLOGY BACKGROUND

Additive manufacturing is a computer-controlled process that generates three-dimensional objects by building layer upon layer of material to generate a usable, physical item. This contrasts with more widely known manufacturing processes such as subtractive manufacturing, casting, and injection molding. Subtractive manufacturing involves using technology such as milling machines or computer numerical control (CNC) machines to cut material away out of a solid block to form the desired object (Creative Mechanisms 2016). Casting allows for generating formed parts similar to 3D printing, but it does not have the precision or the capability of creating as complex parts as AM does. The process involves pouring molten liquid into a customized mold and allowing the liquid to harden and solidify into the desired shape (Thomasnet 2020). Injection molding is very similar to casting in that it involves the solidification of molten liquid into a customized mold; however, this process uses a specific injection mold tool that guides the molten material into the mold (Rogers 2015). The focus of this research report is AM, which uses computer-aided design (CAD) software to deposit material in precise geometric shapes. Through AM, it is possible to create lighter and stronger parts and systems as in the previously discussed traditional manufacturing methods. Further, AM can allow for rapid production, simplified processing, and the development of inexpensive mockups.

Currently, there are seven predominant types of AM technology, including: vat photopolymerization, material extrusion, sheet lamination, powder bed fusion, binder jetting, material jetting, and directed energy deposition (Tofail 2018). Each of these AM technologies has different capabilities that make them appropriate for different applications and environments. There is a wide range of materials that can be used among all these AM technologies, such as plastics, metals, paper, composites, and even edibles such as chocolate.

Additive manufacturing was first brought to the commercial sector in 1987 via stereolithography (SLA). This process uses photocurable resins that harden as a laser draws the shape of the component layer by layer (Hemphill et al., 2019). Once one layer is complete, the platform moves, allowing new resin to fill in the space and be exposed to the laser. This process is depicted in Figure 1. Since this invention, several different types of materials and methods have been developed to broaden AM practices.

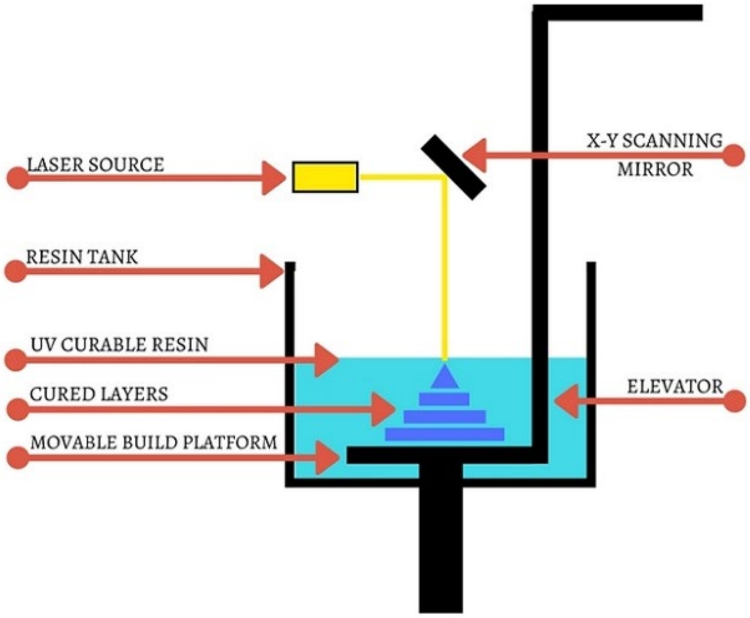


Figure 1. A Diagrammatical Representation of the Workings of SLA. Source: Manufactur3D (2018).

The most common method of additive manufacturing is material extrusion, with the most used extrusion process being fused filament fabrication (FFF), which is more commonly known as fused deposition modeling (FDM). The prototypical 3D printer used across industry, laboratories, and in homes uses the FDM process; therefore, for the purposes of this report, the FDM acronym will be used to refer to this AM method. This method pushes material through a nozzle on a print head, which hardens after being extruded, providing a hard base for the next layer. A graphic of this process is shown in Figure 2. There are several types of thermoplastics that can be used for FDM, such as polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS), which are great for prototyping and quick expendable components; however, they lack the strength characteristics needed for most final products. Additionally, there are composites that are more robust and can withstand harsher environments, such as carbon fiber reinforced nylon.

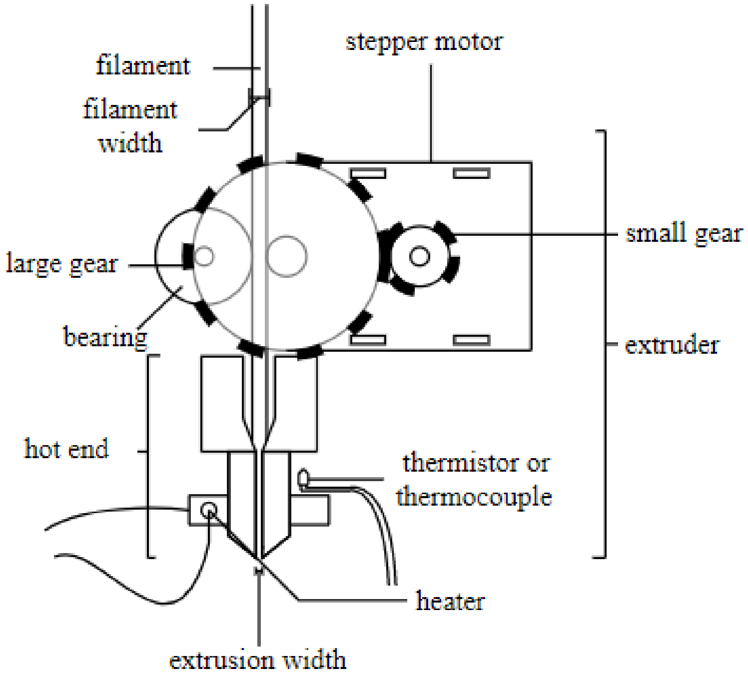


Figure 2. FDM Mechanical Process. Source: Lemio (2011).

Another AM process is directed energy deposition (DED), also known as beam deposition, is an additive manufacturing method which uses a laser beam to melt extruding materials (polymers, powders, ceramics, and metals) as they deposit onto a surface. The DED process is depicted in Figure 3. Like material extrusion, it functions by pushing printing material through a nozzle and onto a surface. However, unlike material extrusion, the printing material is melted as it is deposited, and it can be extruded from any angle because the nozzle can move along more axes than a typical extrusion printer. DED is mainly used for projects where a repair needs to be made to an object (Gibson 2010).

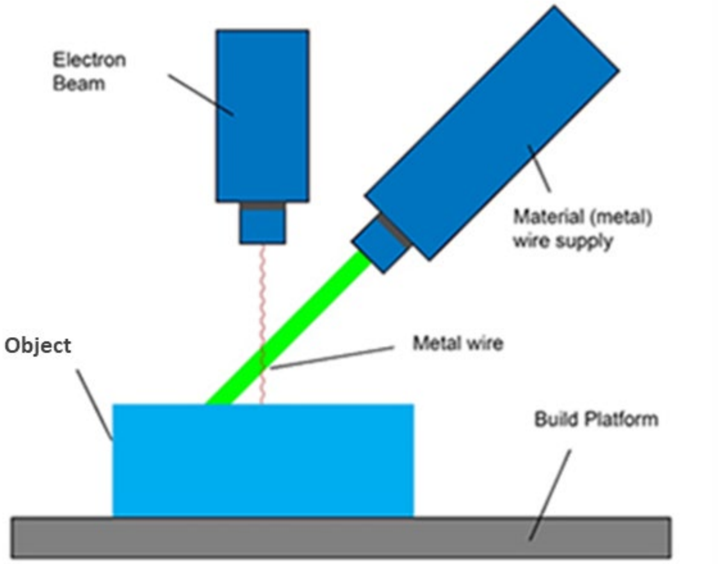


Figure 3. Directed Energy Deposition Process. Adapted from Loughborough University (n.d.).

Though plastics, including composites, are the most common material in additive manufacturing, metal can also be used for components that otherwise were impossible to create prior to AM. Powder bed fusion, the most common method of metal additive manufacturing, depicted in Figure 4, occurs when a thin layer of powder is selectively bonded together by a heat source. Typically, this heat source is a laser, such as selective laser sintering (SLS), selective laser melting (SLM), and electron beam melting (EBM). These parts require some post-processing, but powder bed fusion allows for the development of robust parts for industries such as commercial aviation.

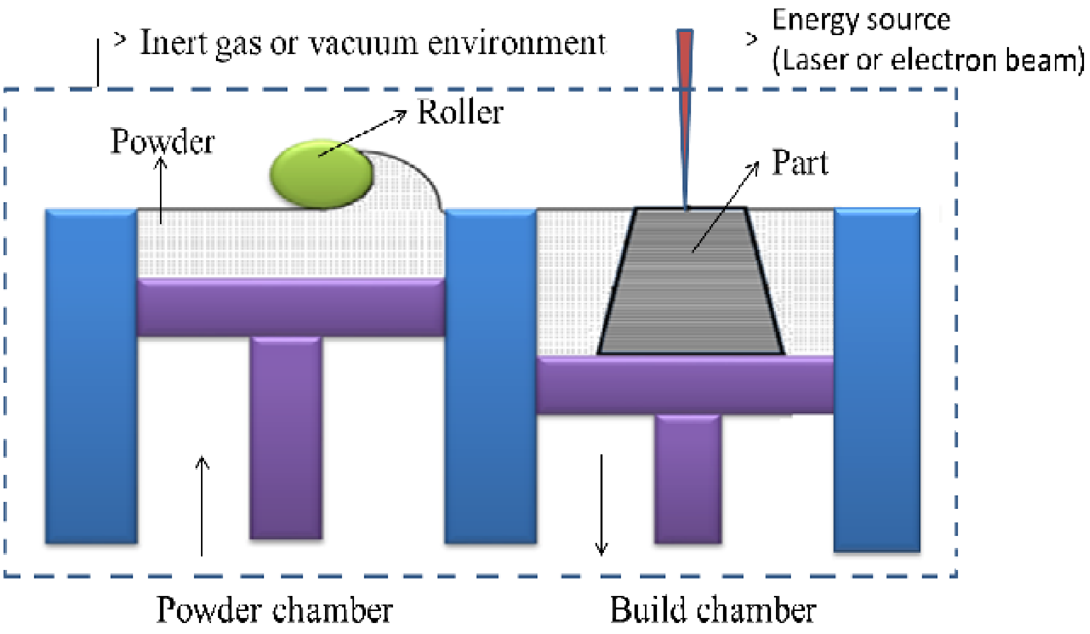


Figure 4. Powder Bed Fusion Process. Source: Bhavar (2017).

Another AM process is sheet lamination, which is the process of stacking and laminating sheets of material to build a 3D object. This process can support several different materials including paper, metal, plastic, and metal or woven fiber composites. Additionally, there are several different types of lamination techniques that can be employed through sheet lamination AM, including: adhesive bonding, thermal bonding, and ultrasonic welding. Sheet lamination is one of the cheapest and fastest AM technologies that exist today; however, it also provides significantly lower additive resolution compared to other AM types (Engineering Product Design 2017).

Additionally, binder jetting is an industrial AM process, depicted in Figure 5, in which thin layers of powder are strategically bonded together using droplets of a binding agent. After the binding agent is deposited, the printing plate lowers, and the process is repeated until the 3D object(s) is generated. Due to the industrial nature of the process, 3D objects are generally created in batches, and much of the unprocessed powder is recycled and used in generating the next item (Additive Manufacturing 2019). This process is used with a range of materials, including the following: sands, ceramics, plastics, glass, and metals. When printing using this method, parts require several post-processing steps due to the low mechanical properties associated with the initial end-product. Some of the post-processing steps include curing the object, filling voids initially left in the product through sintering or infiltration, and finishing by polishing or plating (Additive Manufacturing 2019; Silbernagel 2018).

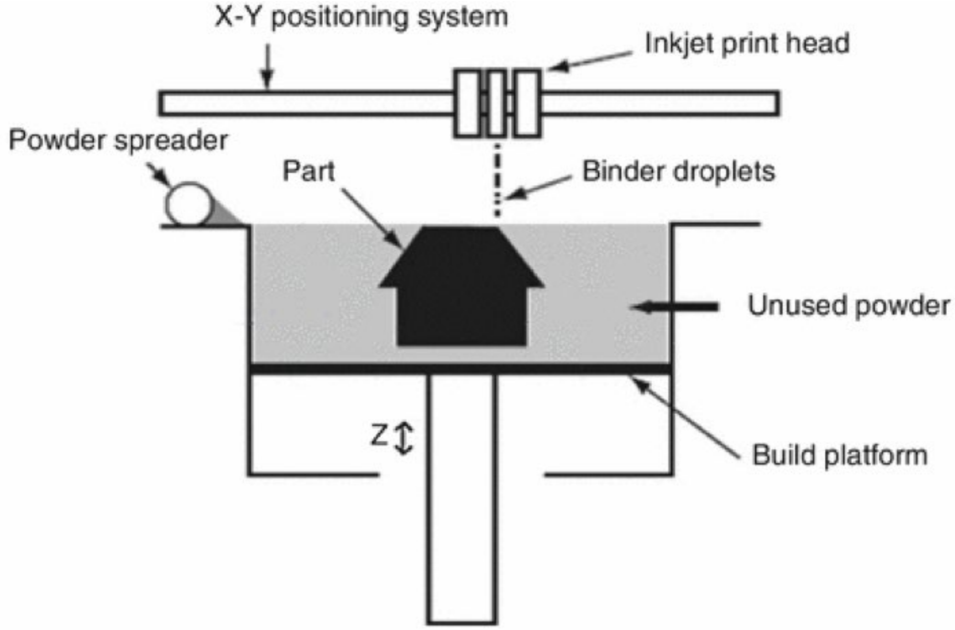


Figure 5. Binder Jetting Process. Source: Silbernagel (2018).

Lastly, material jetting is an additive manufacturing process that uses a thermoset photopolymer resin, as shown in Figure 6. The process consists of a print head that jet polymer droplets onto the build surface and an ultraviolet (UV) light that follows the print head to cure the resin. After the complete layer is printed the build surface drops and the next layer is completed; this is repeated until the object is complete. Material jetting allows for multiple print heads to print numerous materials allowing for greater variety of printed parts by either color or material and use of dissolvable support material. Additionally, objects often require less finishing work as they can be printed in either a glossy or matte option. Given the limitation of using only thermoset photopolymers, parts printed via material jetting are mainly suited for non-functional prototypes.

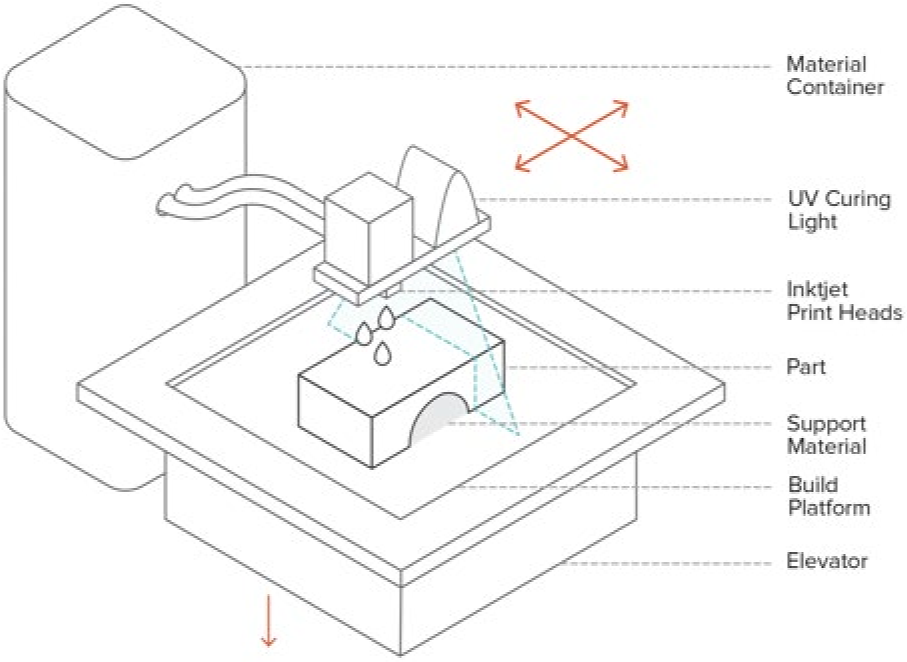


Figure 6. Material Jetting Process. Source: Varotsis (2020).

B. DESIGN CONSIDERATIONS FOR ADDITIVE MANUFACTURED PARTS

While additive manufacturing has made the fabrication of complicated parts easier, there are special design considerations that are unique to AM, and particularly dependent upon the AM process and even the specific machine. Traditional design practices, such as 3D CAD, and computational methods for strength and life cycle are vastly different for additive manufactured components compared to traditionally fabricated parts through subtractive machining, casting, or molding. Some design considerations and concerns include delamination, overhang, component strength, and orientation.

Since additive manufactured parts are constructed layer by layer, delamination can be a major source of failure. This failure mode is particularly apparent in specific processes, such as FDM (Steuben 2015). This failure made can become even more pronounced in the FDM AM method depending upon the material type, fabrication temperature, and part design.

Another major design consideration is overhang—while creating parts with overhangs or cavity features is an advantage of AM, these features can also be prone to flaws. As the material is built up, the weight of the overhang region can cause warping, especially in high temperature fabrication (Fernandez-Vicente 2015). Overhanging features can be supported through the use of support lattices or support columns, whether using breakaway material or specialized support material (Steuben 2015). Support material is a feature of some AM systems that allow a sacrificial material to be used to support the resultant part, however, this material tends to break away from the end-product material or can be dissolved in chemical solutions. Support material can create higher resolution parts, however it also requires longer print times, is more costly per print, and requires more complicated printers.

An additional major design consideration is overall component strength, given that when parts are built using AM, the outer shell is typically the most significant constraint. The infill of the region can be made using a variety of options, including: solid fill (or dense fill), sparse to no fill, cellular structures, or topological optimization (Oropallo 2016). Solid fill is when the machine tries to fill in the infill as much as possible. The success of a solid infill is dependent on the process and material, though typically the part will not retain the strength of a part made from solid raw stock. Sparse fill is the opposite of solid fill, where a component will use as little material for the infill as possible. This will decrease the weight, print time, and material usage of a part, but will also decrease its strength. Cellular structures are composed of repeated geometric designs, such as hexagons or rectangular lattices, to support the part. These geometric infills typically have various parameters such as size and width, which highly influence their overall material properties (Oropallo 2016; Steuben 2015). Topological optimization is computationally intense process in which the infill is specifically design based on material, process, and use case. In order to use this process, the user must be intimately familiar on how the end part will be used and must have the knowledge to establish fine-tuned algorithms (Oropallo 2016).

The orientation in which a part is printed also has a major effect on its properties, especially its strength and resistance to fatigue. Altering the orientation of the print will change the plane for delamination, will modify what features are overhanging, and change the direction of infill structures (Oropallo 2016). It is important to take into consideration a part’s specific use and shape in order to choose an appropriate print orientation.

As in traditional manufacturing processes, a major consideration in the AM design process is the material type. An FDM printer can have the ability to print a variety of materials, and each have advantages and disadvantages associated with them (Steuben 2015). One type of material that alleviates some of the design pressures discussed previously is fiber reinforced plastics (FRP). Fiber reinforced plastics can be used in traditional FDM systems, but due to the fiber support it is not as susceptible to overhang sagging and deforming. In addition, FRP has stronger material properties than most other polymers used in AM (Prüb 2015).

A major constraint in the design of AM derived parts is that traditional 3D CAD software is not built for these manufacturing processes. Further, there are many variables in the design and fabrication process that make it challenging to know the end material properties. Even further is the ability to effectively run physical simulations. Typical finite element analysis (FEA) is done by approximating the structure using geometric shapes, such as triangles or rectangles. As a part becomes more complex, especially with infill designs, these FEA tools become overburdened and less accurate.

Another design consideration for AM parts that can increase the mechanical properties of the final product is post-processing. Depending on the need, AM process, and machine capabilities, there may be some work required to finish the part. This could entail removing support structures, smoothing edges, or removing flaws. Since the lack of post-processing can lead some parts to early failure or poor fits, this design consideration can be crucial when choosing what AM method and machine to use.

C. ADDITIVE MANUFACTURING MATERIAL CONSIDERATIONS

The types of material available to the AM process is continually growing, along with improvements in the use of existing materials. While each material adds benefit to the AM portfolio and capabilities, they can also require special handling to overcome excessive hazards or risks.

Due to the characteristics of the AM process, the material involved may require special handling based on material properties. For example, the materials used in stereolithography are cured through exposure to light. This makes the raw material photosensitive. If the material were exposed to light prior to use, it could ruin it prior to use.

Other materials, such as polymers used in FDM are hygroscopic, meaning they absorb moisture. These materials can vary at the rate and amount they absorb liquid. Through this absorption, the material will not only have a higher water count but also expand in size. This can affect the materials layer adhesion, part tolerance, and even make the material unusable over the course of time. This affects different polymers at different rates, for instance materials such as nylon are very susceptible to moisture and can be compromised in as little as 15 hours (Wassler 2020). Due to the exposure sensitivity of some materials, a component’s verification will need to be based on its handling and precautions.

Another special consideration of material used in AM, are the inherent hazards related to specific materials. These hazards can range from gases, particulates, and chemicals generated when heating the raw material during the AM process (Chen 2020; Haung 2012; Roth 2019). As pointed out in Haung 2012, new materials are being developed and the lack of industry standards make it challenging to fully understand the health consequences. When handling these materials, proper personal protective equipment (PPE) should be maintained, and the material should be handled by properly trained operators.

Long-term environmental effects need to be considered as well, including those not fully understood yet (Bours 2017). The complete life cycle to these parts, from raw material sourcing to excess and waste material disposal, and final product disposal need to be factored into the AM system and its use conditions.

Lastly, many AM materials are combustible and the processes creating or using dust lead to the potential of explosions (Trujillo 2018). The type of materials, safety measuring, handling, and mitigation techniques need to be explored prior to implementation. Further, this can limit the environment in which some systems should be used. Guidelines, training, and standard operating procedures (SOPs) should be developed for AM systems that use or produce combustible dust.

D. USE OF ADDITIVE MANUFACTURING IN THE DOD

Since 2012, AM processes have been used to enhance maintenance and sustainment throughout the DOD. By 2015, the Government Accountability Office found that the DOD took steps to implement AM but did not sufficiently track or document their efforts. However, by 2016, each branch of the DOD had created technology roadmaps associated with AM, which included a description of future of AM within each branch and the gaps between the current state of the practice and future plans (Hull 2019). Additive manufacturing capabilities are already in use throughout the DOD within testbeds, research labs, combat support groups, and deployed within systems such as in the Expeditionary Lab (Ex Lab) of the Rapid Equipping Force (REF) within the Army.

In 2017, the Department of the Navy (DON) AM Implementation Plan V2.0 was released to align current naval AM efforts, and to establish two formal goals for the future of AM within the Navy: “Increase Readiness/Sustainment and Enhance Warfighter Capabilities” (Department of the Navy 2017). Additionally, the plan includes five supporting objectives that will significantly contribute to the Navy’s ability to achieve the overarching goals. The objectives enumerated in that document on page 4 include:

1. Develop the capability to rapidly qualify and certify AM components.
2. Enable end to end process integration of secure on-demand manufacturing with integrated digital AM data, infrastructure and tools.
3. Formalize access to AM education, training, and certification for the DON workforce.
4. Develop responsive AM related business practices, contracting, intellectual property, legal, and liability guidance.
5. Enable manufacturing agility through low volume production in maintenance and operational environments.

Fulfilling these objectives significantly increases the DON’s ability to increase warfighter readiness and sustainment, as well as enhance warfighting capabilities. For example, providing the warfighter with the ability to produce repair parts and components in an operational environment empowers them to be more self-sufficient and not as heavily dependent on the traditional supply chain. Similarly, integrating digital AM data, infrastructure, and tools will streamline the ability to develop customized solutions to challenges that arise in the operational environment, which will ultimately enhance warfighter survivability (Department of the Navy 2017).

Currently, warfighters have capabilities for machining metal parts in the field by using milling machines and lathes; however, these capabilities are limited, especially in expeditionary environments. The skillset required to master these processes is high, and these tools have limitations in what experienced machinists can accomplish. Further, these methods require a significant amount of stock material to operate properly. Consequently, this can result in logistical issues for maintaining and sustaining appropriate levels of stock material and produce large amounts of waste. Using metal AM machines helps limit the amount of material that needs to be used and allows the fabrication of complex parts. However, there remains the limitation of the post-machining process, which typically involves the use of subtractive manufacturing (Zelenski 2019).

An example of a solution that uniquely employs both AM and subtractive manufacturing techniques is the Expeditionary Manufacturing Mobile Test Bed (EXMAN), developed jointly by the United States Marine Corps (USMC) and the Space and Naval Warfare Systems Center Pacific (SPAWAR). The mobile laboratory consists of three major parts, including: a computationally intensive computer that contains complex design software, a milling machine, and a 3D printer. EXMAN utilizes machining with dual heads to address the issue of post-machining 3D printed parts. The dual-head design allows for one head to be used for printing and the other for milling. This eliminates the need for separate post-processing equipment and reduces the system's logistical footprint, allowing the manufacturing process to occur in one step. Further, this system is simple to use and requires minimal training compared to traditional AM techniques such as the traditional metal AM process described previously. This system is being developed within the 1st Maintenance Battalion, specifically to address resupply of parts in the field that have difficulty reaching the warfighter in a timely manner (Zelenski 2019).

The EXMAN system was able to demonstrate its support capability at the Steel Knight event at Palm Springs in 2016. Through this exercise, EXMAN was able to provide live support to the Marines participating in the exercise as they experienced component failure. These failures would have typically taken the warfighter out of the mission, sometimes for over a year while waiting for a new part. Instead, EXMAN was able to provide repair parts in as little as a few hours or one or two days (SPAWAR Pacific 2017).

The Marine Corps Systems Command (MCSC) and the Marine Corps Installations and Logistics Team out of Camp Lejeune have also made advances in the realm of AM. The Expeditionary Fabrication Facility (X-FAB) is a 20 ft. by 20 ft. mobile shelter that supports AM capabilities from design to fabrication. It includes a computer with 3D CAD capability, a 3D scanner to generate models from existing parts, and a 3D printer. This system was designed by the 2nd Maintenance Battalion to fabricate design and repair parts in the field (Randolph 2017). Unlike the EXMAN, X-FAB will not necessarily operate as its own stand-alone AM capability. Rather, the vision is for X-FAB to be used to supplement USMC intermediate-level maintenance shops that already use an existing shelter that is designed to repair parts and weapons, known as the Shop Equipment, Machine Shop (SEMS).

In addition, the benefits of AM can even go as far as building up complete systems and/or buildings. For example, the Office of Naval Research (ONR) has been developing an unmanned aerial vehicle (UAV) for the Marine Corps where all non-electrical components can be generated through AM. This will allow for less spare components to be carried within the field, a decrease in logistics and administrative dependencies due to fewer parts, less dependence on industrial supply, and the ability to fluctuate supply based on demand. Additionally, the MCSC is partnering with the Advanced Manufacturing Operations Cell (AMOC) and the Defense Innovation Unit (DIU) to develop a prototype for an infield AM capability to develop buildings (Washburn 2020). In turn, this capability could reduce material, time, personnel, and training required to construct new facilities in the field, and open the possibility of autonomous construction, removing the warfighter from the vulnerable position of building shelters. In short, the warfighter needs to always remain operationally available and mission ready, and AM is a tool that can bring simplicity, efficiency, and empowerment to the expeditionary forces.

E. SYSTEMS ENGINEERING BACKGROUND

The systems engineering process involves looking at a central issue and solving it in a logical, definable manner. The specific systems engineering process chosen for a particular project depends on the nature of the system application, as well as the experiences of the team members (Blanchard and Fabrycky 1990). Several different systems engineering processes were considered for the purposes of this project, including the "Vee" Process Model, Spiral Process Model, and the Waterfall Process Model.

The classic "Vee" Process Model shown in Figure 7 was originally developed by Forsberg and Mooz. Although several modified "Vee" Process Models exist today that expand upon the original version. This model begins with the defined and decomposed user needs on the left-hand side and ends with an integrated and validated system on the right-hand side. The activities of the left-hand side of the "Vee" focus on resolving the system architecture and developing details of the design. The activities of the right-hand side of the "Vee" focus on verification and validation of components and sub-systems, which flow into a fully integrated system. The middle portion of the "Vee" Process Model shows that testing occurs continuously throughout development to ensure that components and sub-systems are meeting system specifications identified in the system requirements document.

Despite its benefits, however, the "Vee" Process Model was not a suitable fit for this project due to its inflexibility and rigidity. The model requires that the testing documentation is written in tandem with the development phases. While this model would work well for projects that have defined requirements at the outset, it would have been difficult for the research group to implement this process because the requirements changed throughout development based upon stakeholder needs and feedback. The "Vee" Process Model would have required the group to modify the test plans and documentation each time there was a change to the requirements, which would not have worked well for this resource and time-limited project.

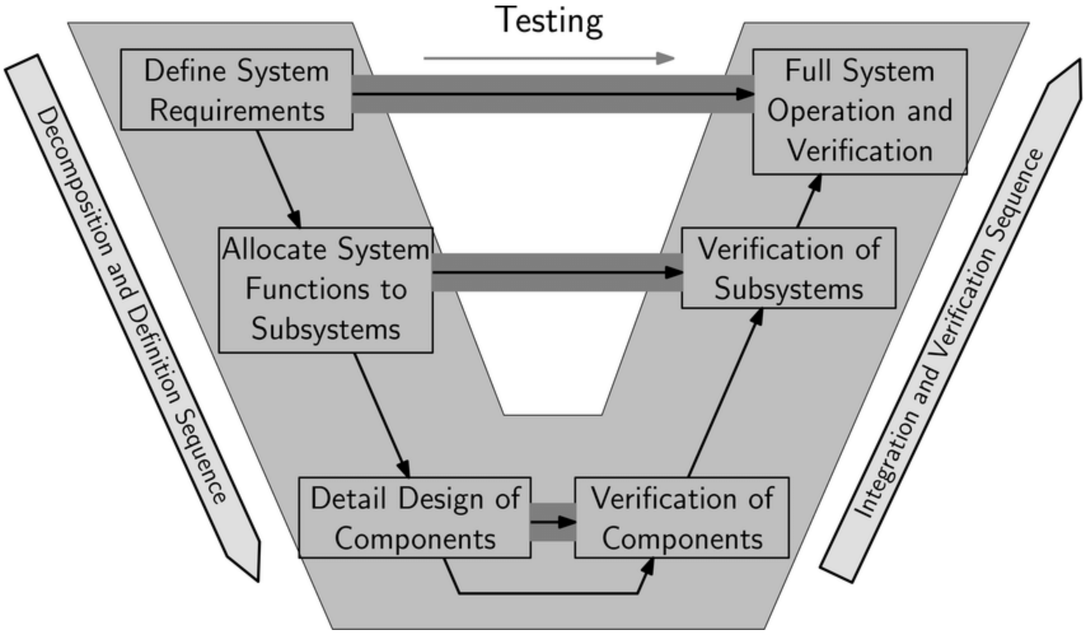


Figure 7. Classic "Vee" Process Model. Source: Blanchard and Fabrycky (1990).

The Spiral Process Model shown in Figure 8 was originally developed by Boehm in 1986 and provides a risk-driven development approach by adapting the Waterfall Process Model to include the incremental development of prototypes. The biggest benefit of using this method is that it allows for an evaluation of risk before preceding into the next phase. Risk is evaluated by delivering incremental and iterative prototypes to the end-user(s) and soliciting feedback after each delivery. This process allows for the enhancement of system functionality and reliability over time, while including the end-users as part of the entire development process. However, it was determined that the Spiral Process Model is not suitable for this project due to time constraints and the lack of stakeholder availability to provide continuous feedback. While this method would work well for a multi-year software-heavy project, it was not feasible to produce several prototypes and incorporate customer feedback on each prototype within a six-month period. Additionally, this model increased the risk of scope creep significantly, which would have hindered the team's ability to deliver the final product in a timely manner.

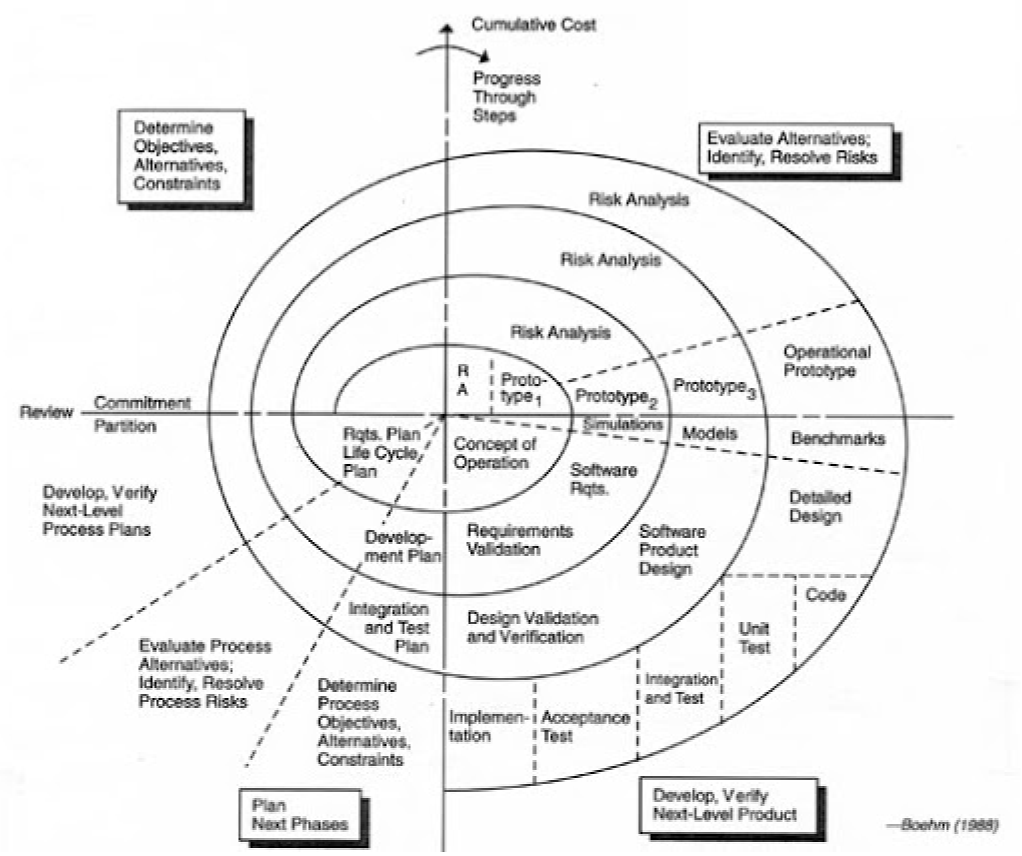


Figure 8. Spiral Process Model. Source: Blanchard and Fabrycky (1990).

Given our analysis, it was determined that the model that best fits this project is a modified approach to the Waterfall Process Model. The original Waterfall Process Model was introduced by Winston Royce in 1970 and was traditionally used for software development projects (Blanchard and Fabrycky 1990). The original model is criticized because it did not provide a means to incorporate changes in the overall systems engineering process or accommodate changes in requirements that occur throughout the engineering process. Traditionally, this model includes baselining the requirements in the beginning stages of the project without any opportunity for modification downstream.

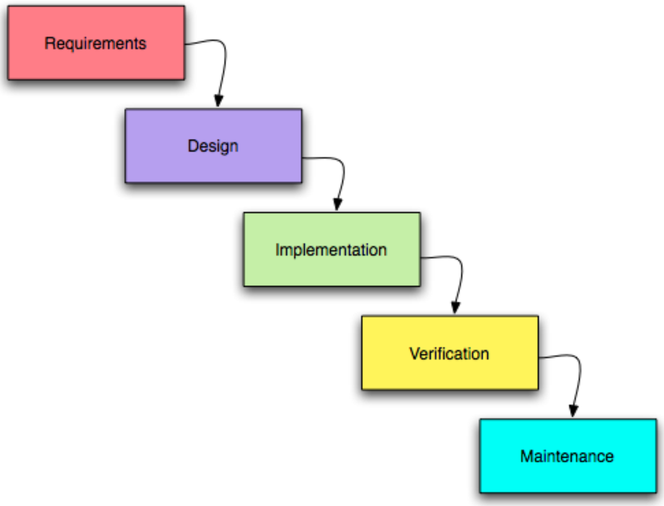


Figure 9. Classic Waterfall Process Model. Source: Blanchard and Fabrycky (1990).

F. SYSTEMS ENGINEERING APPROACH

It was determined that the model that best fit this project is a modified approach to the Waterfall Process Model. Although it is a sequential model, the modified approach provided the opportunity to incorporate feedback and return to previous phases as necessary throughout development, to address any unforeseen deficiencies or challenges. The Waterfall Process Model provides for clear transfer of information from one milestone to the next and discourages moving to the next phase until the preceding phase is reviewed and verified, which served this research-heavy project well. One of the key reasons this model was selected is the modified feedback mechanism that allowed the NEAM team to progress through each stage of the process, while receiving continuous feedback from the stakeholders. This consistent feedback from the stakeholders was advantageous, because it reduced the risk of not meeting or misunderstanding the project goals. The modified Waterfall Process Model used for this project is shown in Figure 10 and is followed by a description of each phase.

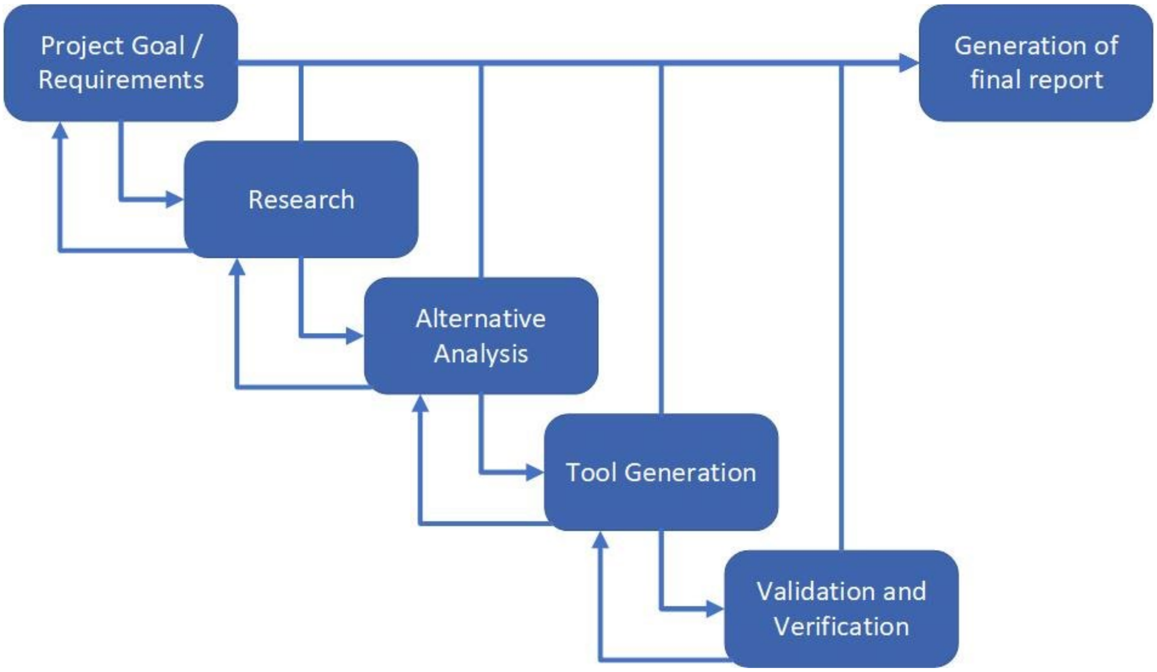


Figure 10. Modified Waterfall Process Model

The various stages for the modified Waterfall Process Model include building the requirements and setting goals, research, alternative analysis, tool development, validation and verification, and the generation of the final report and deliverables. Each of these stages were tailored to the NEAM project as described in the succeeding paragraphs.

The Requirements and Project Goals step focused on two goals. The first is understanding and accurately defining the additive manufacturing system operational requirements, which are derived from the mission definition and system objectives; the requirements and project goals were reviewed extensively with all stakeholders to ensure that the team accurately captured stakeholder needs with respect to topics including, but not limited to: performance and physical parameters, operational deployment or distribution, operational lifecycle, utilization, effectiveness factors, and environmental factors. The second goal is defining the end user requirements of the database and analysis tool. This included capturing stakeholder needs with respect to user interface, selection process, computer hardware and operating system capabilities, storage requirements, information protection, and expected user experience level. Information on trade space within project requirements was collected simultaneously and recorded for use during the Alternative Analysis step.

The Research step entailed gathering information on current and prospective AM methods and applications through detailed literature reviews that span current AM capabilities, applications of AM within industry, and specific DOD capabilities and limitations. Furthermore, the team met with multiple technical points of contacts (POCs) and subject matter experts (SMEs) to better understand how AM is used within the field. Using the knowledge gained from literature reviews, research, and interviews, the NEAM team determined which AM methods and technologies were within scope of the project. The modified Waterfall Process Model allowed the team to continuously work with the stakeholders to refine the requirements throughout the Research step.

The Alternative Analysis step involved researching software options to develop the database and analysis tool. The goal of this step is to identify all the potential software options that could be used to satisfy the defined requirements. For us to make an informed decision, each software option was critiqued and evaluated by the team. The team down-selected the software alternatives to identify the best software to use to build the tool. The down-selection was based on two key attributes— the ability of the software to build the tool and the ability of the software to meet the stakeholder needs and requirements for the tool. After the team identified the best alternative, the analysis process and final software selection was discussed with the stakeholders for approval. Additional detail related to the software development process for the tool can be found in Chapter IV.

The tool was developed using the selected software during the Tool Generation step. Within this step, an agile software development methodology was used to generate the tool, starting with basic functionality and expanding to cover all stakeholder requirements. Additional information on the implementation of the agile process can be found in Chapter IV. Throughout development, the NEAM team addressed bugs in the tool by implementing an iterative error checking process. Error checking occurred each time the tool functionality was expanded to ensure the tool was functioning correctly during each stage of agile software development.

The Verification and Validation step ensured that the tool met the project requirements (verification) and ensured that the tool met stakeholder needs (validation). The V&V methodology confirmed that the final tool met each stakeholder requirement or need by testing, inspection, or a combination of both. Specific test scenarios were developed for requirements that could be verified using clear inputs and outputs. Inspection was used for all requirements where testing was not feasible such as user interface requirements or maximum/minimum quantities of database entries. The tool generation step was revisited to address gaps in tool capabilities during V&V testing. A comprehensive requirements verification & validation test matrix (RVTM) can be found in Chapter VI, Section B that includes traceability of test cases to specific project requirements.

The last phase of the modified Waterfall Process Model involved generating the final report, as well as all other final deliverables associated with the project including the User Guide and tutorial videos. This is a crucial step of the SE process because delivery of all the project artifacts ensures that the stakeholders are fully informed and provides them with the opportunity to update or modify the deliverables as new information/data becomes available.

III. STAKEHOLDER AND REQUIREMENTS ANALYSIS

This chapter describes the specific stakeholders that will benefit from this work, their involvement and interest in the project, and respective stakeholder needs and expectations. Additionally, this chapter discusses the requirements analysis process that was used by the NEAM Team to translate stakeholder needs into specific system requirements. Finally, this chapter discusses existing AM capabilities and the gap analysis that was conducted to determine the priorities for this effort.

A. STAKEHOLDER IDENTIFICATION AND ANALYSIS

The Defense Acquisition Guidebook defines stakeholder as "any group or organization with a related or subsequent responsibility that is directly related to the outcome of an action or result." In other words, stakeholders have a level of interest and/or influence that can impact the overall project (Department of Defense [DOD] 2016). Therefore, it was critical to involve the stakeholders early in the planning and problem definition stage of this project. This allowed the development team to better understand their needs and expectations, which had a direct impact on the requirements.

Stakeholders can be classified into two categories—primary and secondary. Organizations or people who are identified as primary stakeholders will be directly impacted by the project decisions or actions, while secondary stakeholders will be indirectly impacted by the project decisions or actions. The primary stakeholders' needs are prioritized and incorporated into system requirements, architecture, and design throughout the course of the project. The secondary stakeholders' needs are captured to the greatest extent possible but will only be addressed if schedule permits.

The three primary stakeholders for this project include: the NECC, the NAVFAC Engineering Expeditionary Warfare Center, and Naval Postgraduate School (NPS). The NECC is the topic sponsor for this effort and is responsible for integrating warfighting requirements for combat and combat support elements in expeditionary maritime environments. The NECC has a vested interest in this project because they plan to use the resultant studies and deliverables to better integrate AM capabilities into the greater naval mission, and efficiently interoperate future capabilities with existing ones. The NAVFAC Engineering Expeditionary Warfare Center is a primary stakeholder that supports the development and fielding of systems for the NECC and is also the lead organization tasked to develop an AM program of record. The NPS is the organization tasked to develop and deliver a solution to the research questions posed by the NECC for this project. The NPS is qualified to conduct this research as it is nationally recognized for its Center of Additive Manufacturing. The faculty's diverse set of expertise will ensure that the domain is treated comprehensively and that first, second, and third-level effects are accounted for in the research.

There are several other secondary stakeholders which may have an indirect interest in the results of this project. Table 1 provides a stakeholder overview, including prioritization, and level of involvement and interest in the NEAM project.

Table 1. Stakeholder Analysis

Stakeholders	**Type Prioritization (Primary/ Secondary)**	**Level of Involvement in NEAM**	**Interest in NEAM & Primitive Need**
NECC	Primary	Primary stakeholder for the NPS led NEAM project.	Interested in deploying interoperable AM equipment in DMO, LOCE, EABO environments to improve warfighting capabilities and maximize ROI.
NAVFAC Engineering Expeditionary Warfare Center	Primary	Develops, fields, and supports systems for the NECC and other expeditionary forces.	Interested in advancing AM into the combat enterprise and influencing AM requirements and investment decisions.
Naval Postgraduate School	Primary	Conducts research and development to support U.S. warfighting advantage. Provide defense-focused	Interested in developing new approaches and systems for naval Additive Manufacturing. Interested in developing

Stakeholders	Type Prioritization (Primary/ Secondary)	Level of Involvement in NEAM	Interest in NEAM & Primitive Need
		academic knowledge to future system engineers for DOD.	trained systems engineers to support DOD.
N95 (Expeditionary Warfare)	Secondary	Develops requirements, sets priorities, and provides programmatic and technical direction to support expeditionary warfare systems.	Interested in recommendations for improving the readiness of expeditionary warfare systems and conduct of amphibious warfare.
Naval Additive Manufacturing Executive Committee (NAM EXCOMM)	Secondary	Annually updates the DON AM Implementation Plan to reflect progress and planning activities and establishes AM policies, procedures, and standards.	Interested in understanding current and future DON AM capabilities to inform resourcing decisions and updates to the DON AM Implementation Plan.
Office of Naval Research (ONR)	Secondary	Coordinates and executes science and technology efforts and programs for the U.S. Navy and USMC.	Interested in creating and developing AM materials and processes for naval applications.
Warfighters	Secondary	Operational involvement and/or understanding how to identify components that can be developed using AM technology.	Interested in the most effective and suitable AM technology to deliver rapid equipment and ensure operational flexibility.
AM Manufacturers	Secondary	Implement and develop AM technologies and techniques to create lighter and stronger parts and systems for the DOD.	Interested in providing high-quality products to DOD customers.
DOD Contractors	Secondary	Translate the needs of the DOD into requirements for effective warfighting systems and identify potential AM technologies.	Interested in providing the government with AM support and integration into the fleet.

Stakeholders	Type Prioritization (Primary/ Secondary)	Level of Involvement in NEAM	Interest in NEAM & Primitive Need
PEO Ships	Secondary	Executes the design and construction of all destroyers, amphibious ships, special mission and support ships, and special warfare craft.	Interested in shortening lead-times for the replacement of ship components and parts.
Fleet Marine Force	Secondary	Operational involvement in performing offensive amphibious or expeditionary warfare and defensive maritime employment.	Interested in the most effective and suitable AM technologies to ensure operational flexibility for the fleet.

B. STAKEHOLDER NEEDS

In order to develop detailed and effective system requirements, it is vital to first understand stakeholder needs and expectations. The team hosted a kickoff meeting with the NECC to gather a full account of the stakeholder needs and establish a common baseline for the project. Those needs were then transformed into specific requirements to help scope the project appropriately. The following stakeholder needs were identified during the kickoff meeting:

- AM capabilities for replacement parts (existing equipment and tools)
- AM capabilities for construction operations (custom structure/concrete printing)
- The ability to push as much capability and capacity as possible to units in theater to support major combat operations
- AM components that can serve as temporary fixes or bridge solutions when the supply chain for replacement parts is strained or slow

- The ability to develop a parts library of (digital files with 3-dimensional (3D) descriptions of the parts)
- A well-documented decision-making process and tool with the ability to insert updates with new information
- Dispersion plan for how best to employ different AM assets amongst the Navy fleet and USMC

C. ASSUMPTIONS

After researching the current available AM technology, the team identified, discussed, and approved project assumptions with the stakeholders; the information was related to the AM deployed system location, use, and lifecycle. These assumptions were used to identify specific AM systems that were included in the database. The assumptions were sorted into four categories:

1. AM Deployed System Location Assumptions

- The AM system will be used in forward operating base (FOB) and advanced naval base (ANB) environments.
- The AM system will be utilized in a space that limits the exposure to elements, (i.e., under a canopy for rain or within an enclosure for sand and dust).
- The AM system will be capable of being shipped/transported to area of use.
- The location will enable a proper disposal of any byproduct of the AM process.

2. AM Deployed System Use Assumptions

- The AM system will be used to produce parts for replacement with compatible software that will be available at the location of use.

- The AM system will undergo regular maintenance to ensure proper working order.

- The AM system will be used according to proper use guidelines (directions) and will not be used for purposes other than AM.

- The AM system will include self-diagnostic software to identify errors and assist in troubleshooting efforts.

- The user of the AM system will be properly trained on the system.

- The AM system will have calibration procedures in place to prepare the system for 3D printing.

- The AM system will have a secure printing procedure in place to ensure a print is not interrupted (e.g., someone accidentally hits a computer keyboard or the computer goes to sleep).

3. AM Deployed System Lifecycle Assumptions

- The AM system will have a limited life because of continuous growth in AM technology, which leads to obsolescence.

- The AM system will be maintained at the location and should include appropriate spare parts based on likelihood of need.

4. AM Analysis Tool and User Assumptions

- The analysis tool will be maintained with updated, applicable AM technologies.

- Users of the analysis tool will understand the specifications of the components they intend to manufacture.

- Desired AM parts will have available 3D files needed for the process of 3D printing (manufacturing).

- Users of the analysis tool will follow the training and instructions provided by the NEAM team.
- The analysis tool will provide AM technology recommendations based upon the data inserted by the user.
- The user of the analysis tool will have a functional understanding of the Microsoft Excel application.
- The user of the analysis tool will have a functional knowledge of AM technology.
- The analysis tool will assess AM capabilities only and it will not provide recommendations for other manufacturing capabilities in hybrid systems.

D. EXISTING CAPABILITIES

AM system solutions have been embraced on continental United States (CONUS) bases throughout the DOD as they are inexpensive and relatively easy to use, while addressing the urgent needs of the military forces – the production of the physical parts when and where they are needed. Most of these systems include low-cost commercial-off-the-shelf (COTS) systems such as the extrusion printers LolzBots and MakerBots (Fuentes 2019). Because of their low cost and ease of use, these systems have been purchased for experimentation and preliminary testing of their capabilities without much thought given to their long-term support. In principle, that approach may be adequate for a specific group's needs. However, the same approach is not optimal on a larger scale, such as the entire DOD or one of the DOD services. While warfighters may be trained and familiar with AM capabilities, the capabilities of AM systems are not uniform, and therefore, training may be redundant and the likelihood of using the system incorrectly increases. Having a wide range of systems will create a group of low-level experts and experts for a narrow group of systems rather than AM system experts who are versatile at the broad capability level.

As previously discussed, there are efforts within the DOD to create infield laboratory systems, including the Ex Lab (short for Expeditionary Lab) construct in the U.S. Army and EXMAN and X-Fab in the USMC (SPAWAR Pacific 2017; Zelenski 2019; Randolph 2017; Nesaw 2020). These systems and approaches focus on creating mobile manufacturing capabilities, which includes AM; these same capabilities can be utilized at bases CONUS, outside continental United States (OCONUS), and even remote operating bases. These systems are composed of multiple mobile containerized shelters, allowing for ease of mobility. While these systems include AM capabilities, there is no unified effort - each system has its own criteria and its own operational mission. This is especially apparent in the dual systems that have been funded by the USMC.

Likewise, an afloat AM capability exists on the USS John C. Stennis within the additive manufacturing laboratory (AML). This lab contains 3 types of 3D printers (Stratasys uPrint SE Plus, LulzBot taz-6, and MakerGear M3), a laser scanner (Artec Eva) and laser engraver (Boss Laser Engraver LS-1630), and a benchtop CNC mill (Tormach PCNC 400) (Nicholls 2019). These capabilities and tools supported by those facilities include manufacturing of various components, from 3D printing of plastic components, engraving and cutting plastics and thin metals on the laser engraver, to machining plastics and metals on the benchtop milling machine. However, one common theme amongst these tools from end-user feedback is that they all have usability issues. This is indicative of prematurely adapting a new technology prior to thoroughly understanding the requirements, support, and usability.

Since the benefit of the AM capability has been proven on afloat warships (Rammel 2020), the Navy has been looking to broaden the capability to the sub-sea community. It is postulated that new submarine ships will be outfitted with AM systems. However, the submariner is already taking advantage of AM properties by using such systems to produce rails for sliding doors, electrical covers for cable connectors to increase the safety of the vessel, and even cup-holders to help with limited space that is typical for a submarine.

To summarize the current state of AM capabilities within the DOD, clearly there is an engaged and enthusiastic user base that has already taken steps to incorporate AM technology into their domain of operation. The most significant gap that exists today is the need to align the DON and DOD to progress AM technology in a unified effort and provide systemic support for the needs of the greater naval mission.

E. GAP ANALYSIS

The DON AM Implementation Plan V2.0 (2017) defines the goals of AM to increase readiness and sustainment to enhance warfighting capabilities. To be able to properly reach these goals, it is important to understand the capability gaps of AM technology from a technological perspective, as well as from DOD policy. It should be noted that the Navy is not new to the use of AM capabilities in support of their missions; there are currently systems deployed on ships, in CONUS maintenance support, test branches, and in logistics groups. However, the problem lies in not having the uniformed, systemic solutions and methods that can be used by all units across the naval domain. Having a large variety of AM machines, each requiring different training, support software, maintenance support, and usability constraints, diminishes the global effects that AM could bring to the naval domain.

The AM technology provides many benefits to industry and the DOD including cost reductions, faster product availability, and limitless creativity for design, however, this technology has its limitations. They include limited build size, the fidelity of the printed artifacts, limited type of materials that can be used for 3D printing, low print speed (especially in case of the parts with features that require high fidelity), and a need for a test and validation of 3D printed parts and materials.

Parts that are designed and printed by sailors and marines need to go through a validation process to ensure they are properly built for their intended use. Components on DOD systems tend to be mass produced or produced in manufacturing facilities where engineers carefully check their designs. Most AM solutions are very easy to use and do not require expertise in mechanical design and development. Regardless of the ease of use, it is necessary to ensure the parts being designed and 3D printed can withstand a variety of environmental conditions and do not significantly increase cost, time, and operational readiness, thus negating the benefits of AM deployment.

The validation of parts is dependent upon the specific AM system, as they all have different characteristics. For example, AM systems come in many different sizes that allow for small and large prints. Larger machines lead to reduced mobility, while smaller AM technology restricts build size. However, an analysis focused on the specific use of the technology is needed to understand at what point the size of the machine and its capabilities (or a lack of capabilities) will reduce mission readiness for the warfighter.

This project aims to develop a tool to assist decision makers and help close some of the capability gaps when deciding what AM technology best suits their needs and their mission. Having a readily available database of available 3D printers and commonly printed parts will allow AM to be implemented across the naval domain, including the expeditionary forces.

F. REQUIREMENTS ANALYSIS PROCESS

This section of the report elaborates the requirements necessary for developing the database and a tool that helps determine the AM system best suited to support specific user needs and mission. Requirements analysis is the process of identifying user expectations and needs for the system and transforming them into detailed, relevant, and quantifiable requirements. The purpose of requirements analysis is to define and continuously refine the functional and performance requirements of all system elements. Additionally, the requirements analysis process provides a framework to accurately assess the system performance throughout its lifecycle and ensure that the user needs are being adequately addressed. Requirements analysis also provides a mechanism to perform trade-off analyses to determine which requirements should be prioritized to ensure the best quality product is delivered within cost and schedule constraints to meet a specific operational need or mission.

For the purposes of this project, requirements analysis was performed using a set of well-chosen techniques including meetings with the stakeholders, SME interviews, and trade-off analyses. The research group utilized the requirements analysis process as defined by the Defense Acquisition University (DAU), which comprises of the following steps (Defense Acquisition Guidebook 2010, 323):

- Analyze user requirements.
- Translate end-user needs into basic functions.
- Develop a quantifiable set of performance requirements by defining the functional boundaries of the system in terms of the behavior and properties to be provided.
- Define each function that the system is required to perform.
- Define implementation constraints (stakeholder requirements or solution limitations).
- Translate performance requirements into specific system technical design requirements and functions.

G. REQUIREMENTS

1. Top-Level Requirements

1. The decision analysis process shall provide a method to aid a user in analyzing AM systems for use in the following expeditionary environments:

    a. Littoral Operations in a Contested Environment.

    b. Expeditionary Advanced Base Operations.

    c. Distributed Maritime Operations.

2. The decision analysis process shall allow users to input desired data, such as but not limited to the following:

    a. Available AM systems.

    b. AM system characteristics.

    c. User preference on characteristics.

3. The decision analysis process shall provide an output to assist the user in the decision-making process.

2. Functional Requirements

a. Database Functionality

4. The analysis tool shall allow for the inclusion of an AM technology database to support expeditionary missions.

b. Database Content

5. The AM technology database shall include various AM system specifications for the decision analysis process to analyze and provide an output to the user.

6. The AM technology database shall contain but is not limited to the following AM system information attributes:

   a. Build dimensions
   b. Build material
   c. Build process
   d. System dimensions
   e. Print speed
   f. Cooling requirements
   g. Print quality
   h. Post processing requirements

7. The values within an attribute shall all be of the same unit of measure.

8. The AM technology database shall include a user-modifiable sample of available AM technologies at the time of development with a cut-off date of 31 March 2021 for new data. The sample shall include machines that cover a range of available materials and capabilities. At a minimum the sample will include 40 AM systems with the following characteristics:

   a. There shall be a variance in accepted material type (metal, plastic, composites).
   b. Printers with varying print precision (in all dimensions, i.e., x, y z)
   c. Printers with varying print speeds.
   d. Printers with varying filament thicknesses (where appropriate)
   e. Printers with varying hot bed temperatures (where appropriate).

    - f. Printers with varying print qualities (layer thickness).
    - g. Printers with a variance in print bed area (small is considered less than 5in x 5in, medium is considered between 5inx5in and 8in x 8in, large is considered greater than 8in x 8in).
    - h. Printers that require post processing of materials and printers that do not require post processing of materials before parts can be used.

9. The database shall include a notes section for each printer to be filled in at the users' discretion with relevant information not captured in other database categories.

c. Database Updates

10. The database shall not cap the number of AM technologies that can be added.
11. The contents of the database shall be modifiable such that previously entered information can be changed or deleted by the user.

d. Tool Functionality

12. The tool shall allow for the user to add and modify the AM technology database in the following ways:
    - a. The tool shall allow manual additions and modifications of AM systems.
    - b. The tool shall automatically incorporate inputs into the AM technology database.
    - c. The tool shall automatically update the AM technology database without modification to the source code.
13. The tool shall error check the database in the following ways:

   a. Ensure input data is entered correctly (e.g., a letter listed instead of a number).
   b. Ensure a duplication is not listed (e.g., multiple entries existing).
   c. Ensure all required information for an entry is entered.

14. The tool shall allow filtering of attributes in the following ways:
   a. Allow specification of particular attributes to be viewed.
   b. Allow the user to identify specific weights for each attribute.
   c. Display AM technology that best fit the weights provided by the user.

e. User Interface

15. The tool shall have a GUI that allows the user to access functions of the tool:
   a. Add and update the database.
   b. Run the decision analysis tool.
   c. Error check the database inputs.
16. The tool shall notify the user of errors in the data inputs or analysis results.
17. The tool shall contain instructions on user interface features.
18. The tool shall allow the user to modify the selection of attributes, attribute values, and attribute weights without interacting with the source code.

f. Operating System

19. The decision analysis process shall be developed in software that is available to DON users.
20. The decision analysis process software shall be compatible with Windows and OS X operating systems.

21. The application software hosting the decision analysis process shall allow for future development for users to implement source code modifications if desired.

g. System Use

22. A user's guide shall be developed to support users in the decision analysis process.
    a. The user's guide shall include written step-by-step instructions for how to operate the following capabilities of the tool:
        i. How to manually add and modify the AM technology database.
        ii. How to import additions and modifications to the AM technology database.
        iii. How to error check the input data.
        iv. How to assign weights to attributes.

23. A tutorial shall be developed for inclusion with the decision analysis process user's guide.
    a. The tutorial shall include a video demonstration with verbal step-by-step instructions for how to operate the following capabilities of the tool.
        i. How to manually add and modify the AM technology database.
        ii. How to import additions and modifications to the AM technology database.
        iii. How to error check the input data.
        iv. How to assign weights to attributes.

24. The analysis tool and database shall be constructed with open information (unclassified publicly available information), allowing free sharing within the DOD, contractors, and other potential users.

IV. TOOL DEVELOPMENT

This chapter provides an overview of the AMPAT code development process and the software processes that were followed to develop the tool in a timely and efficient manner. Additionally, this chapter provides the rationale behind the data and specific parameters that are included within the tool to conduct analysis. Finally, the tool capabilities are demonstrated in a Capability Taxonomy (CV-2) and the limitations of the tool and database are also described.

A. ANALYSIS PROCEDURE

1. Minimum Viable Product and Modular Software Development

The goal of this effort was to develop the most effective tool for the project stakeholders as efficiently as possible. To accomplish that, the NEAM team used the input gathered from the stakeholder needs and requirements analysis and defined a minimum viable product (MVP). The purpose of defining an MVP is to identify the minimum set of features and capabilities required to provide the stakeholders with a functional and useful product. The team identified the following capabilities as crucial features of the MVP: the capability to filter AM technology selections; the capability to output a list of filtered printers based on user filtering selections; the capability to apply weights to specific attributes; the capability to output AM technology rankings in a graph based upon the weighted attributes; the capability to create and support an AM technology database with details for specific AM systems; the capability to input additional attributes for the tool to use during analysis; and the capability to produce outputs that can be used to inform dispersion plans for AM capabilities across the fleet. It is important to note that the AM technology database that currently exists within AMPAT is represented as a flat list of coefficients for various AM systems the NEAM team identified through literature reviews; it does not contain advanced database management concepts or functionality such as entity relationships.

The benefit of defining an MVP before developing the software is to provide a baseline to develop a comprehensive plan of action that will be used to implement each capability. To this end, the MVP capabilities were partitioned into manageable modules of code so that the developers could build it in an organized and expeditious manner. The AMPAT code separates each AM technology filter into its own function; multiple modules are then used to separate the main capabilities, filters, inputs, and outputs. The modular software design concept was used to allow for functionality to be developed independently in a self-contained environment, enhance the flexibility and customizability of the software, and increase software developer productivity (Hare and Kaplan 2016).

Another benefit of developing modular software is that it is much easier to reuse and extend to other projects than fully integrated code. That is particularly important for this project because it is likely that stakeholders or future NPS students will evolve the tool. The modular software design approach will simplify the process of modifying the tool as necessary to meet the needs of different customers. Additionally, decomposing a program that has many capabilities and features into discrete modules makes it easier to pinpoint the sources of any errors that arise during testing of the code.

2. Agile Software Development Process

We applied a modified agile software development philosophy by defining the MVP, approaching code development with a modular design, and then identifying additional capabilities and features that could be implement in the future. Agile software processes require less preparation than traditional software development processes by breaking tasks into small increments; that allows the developer to quickly add functionality to the MVP (Sharma et al., 2012). Once the MVP was complete, the team transitioned their focus to the development of additional capability into the tool in the form of agile sprints.

Agile sprints are fixed durations of time in which specific work must be completed. The agile sprints were defined by analyzing and prioritizing the stakeholder requirements that were not satisfied by MVP development to create a product backlog (Sharma et al., 2012). Next, the NEAM team divided up the remaining desired functionalities outside of the MVP into independent agile sprints. A sprint backlog was created to define the feature or capability that each sprint should address (Sharma et al., 2012). In traditional agile development projects, sprints are limited to 30 days; however, to maintain the schedule for this project, the maximum duration for each sprint was seven days (Sharma et al., 2012). After each sprint was completed, a new increment of the AMPAT was released to the internal development team and tested to ensure that it was functioning as expected. Due to the project's time constraints, the NEAM team was unable to follow the typical agile software process of releasing the tool to the stakeholders after each sprint for feedback. Figure 11 provides a visual depiction of the agile sprint development process that was used to incorporate additional functionality into the AMPAT.

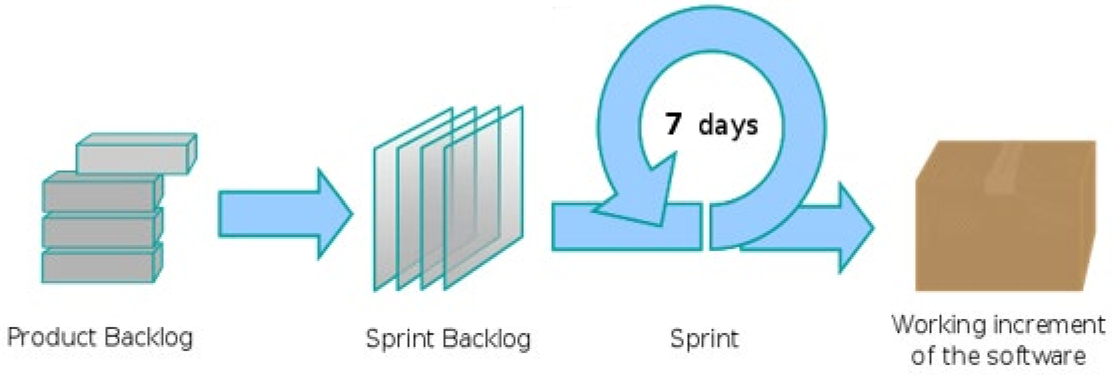


Figure 11. AMPAT Agile Sprint Development Process. Adapted from Data Science Project Management (n.d.).

The following development activities were planned to be accomplished using the agile sprint development process. Due to time constraints of the project, only 1a was successfully implemented within the AMPAT. The other activities listed herein are opportunities for future work to evolve the tool's capabilities.

1. Development of the automation capabilities within the tool.
    a. Develop prompts for the user to input database entries.
    b. Develop functionality to allow the program to read-in specifically formatted files (i.e., .csv, .txt).
2. Development of the advanced filtering capabilities.

    a. Develop functionality to allow the user to add new print materials to the tool (e.g., ABS, nylon).
    b. Develop functionality to allow the user to remove print materials from the tool.
    c. Develop functionality to allow the user to add new general material types (e.g., metal, ceramic, plastic) to the tool.

3. Further development of the output capabilities of the tool.
    a. Develop functionality to export graphics to PowerPoint or PDF files.
    b. Develop functionality to automatically generate a basic report of the tool's results.

3. AM Technology Parameters

The NEAM team employed various techniques to define specific parameters and include them in the AMPAT AM technology database. The techniques included: meeting with small focus groups of two to five stakeholders from the NECC, NAVFAC, and USMC to understand their needs for the tool; meeting with qualified AM SMEs, including an evaluator of AM technologies for the USMC and the Chief Scientist of the Advanced Manufacturing Operations Cell to solicit their input concerning the parameters that are important for the use of AM technologies in the field; and extensive literature research and analysis (described in Chapter II), to understand various AM methods. Figure 12 portrays the top four areas of significance from the stakeholder focus groups, SME interviews, and literature reviews. The items shown in the middle of the Venn diagram represent areas of commonality amongst all three techniques.

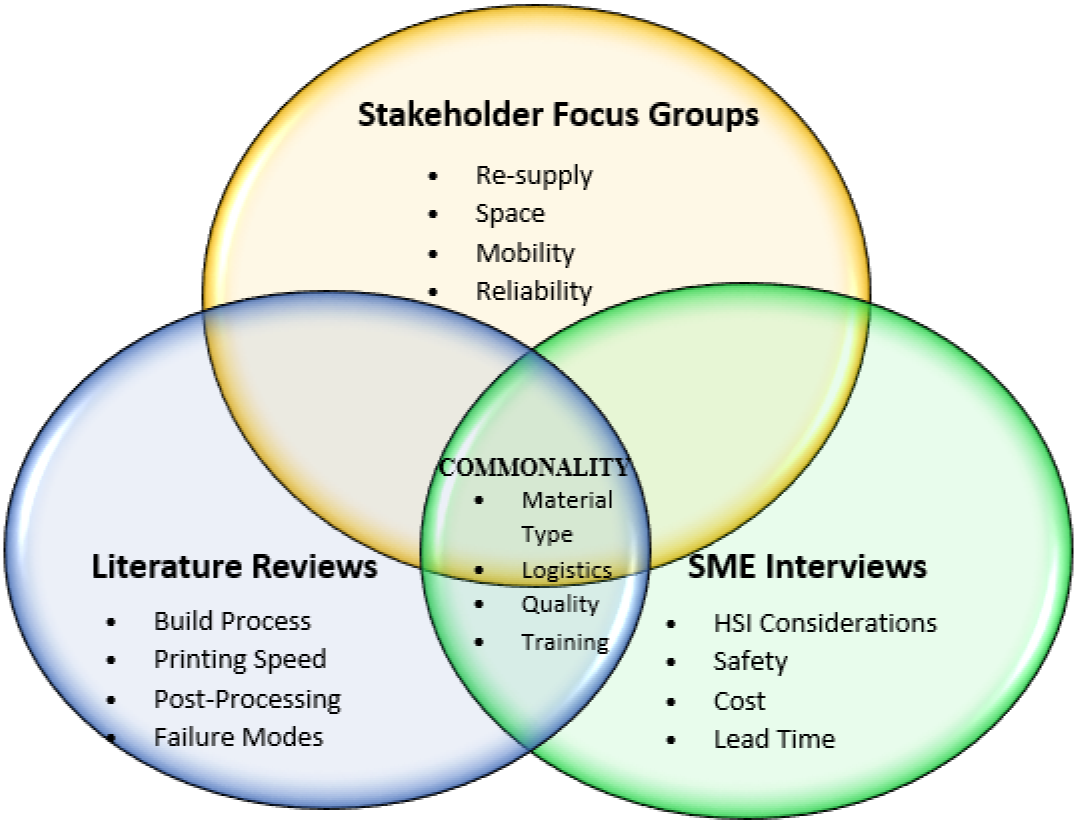


Figure 12. Venn Diagram for AM Parameters of Importance

The NEAM team translated the items identified in Figure 12 into systems engineering "ilities" to include parameters within the AMPAT. Systems engineering "ilities" are also known as key system attributes that serve as criteria that can be used to judge or critique a system's operation (Willis and Dam 2011). According to systems engineering SME and president of SPEC Innovations, Steven Dam, an "ility" is a characteristic of a system that applies across a set of functional or system requirements (Willis and Dam 2011). Table 2 illustrates how the NEAM team decomposed each top-level "ility" into hierarchical sub-groups to identify specific, measurable parameters included in the AMPAT. Each measurable parameter in Table 2 ties directly to one or more AM parameters of importance identified from the stakeholder focus groups, SME interviews, or literature reviews; that ensured the AMPAT parameters are relevant and useful to the project stakeholders.

Table 2. AMPAT Parameters

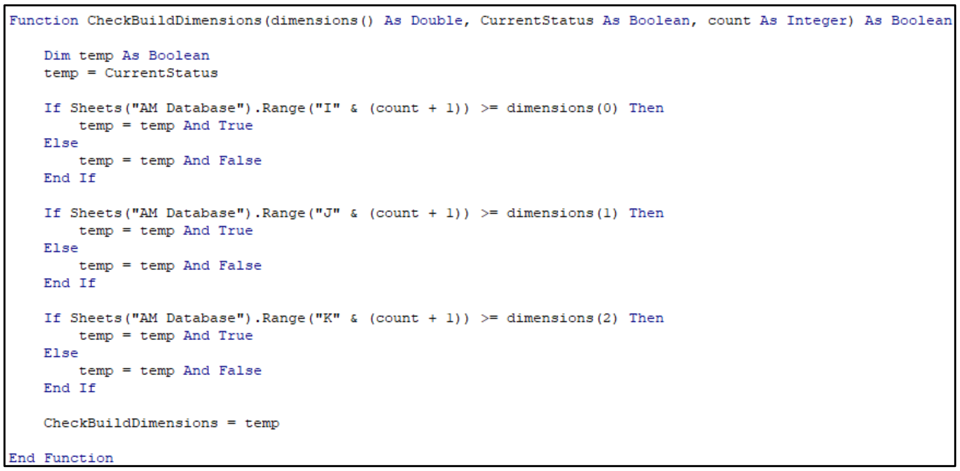
Top-Level "ility"	**Decomposed "ility"**	**Measurable Parameters**	**Units**
Supportability	Reliability	Failure Rate	Hours
		Mean Time Between Failure	Hours
	Maintainability	Mean Corrective Maintenance Time	Hours
		Mean Preventative Maintenance Time	Hours
		Mean Active Corrective Maintenance Time	Hours
		Mean Active Maintenance Time	Hours
		Maximum Active Corrective Maintenance Time	Hours
		Logistics Delay Time	Hours
		Administrative Delay Time	Hours
		Maintenance Downtime	Hours
		Mean Time Between Maintenance	Hours
		Mean Time Between Replacement	Hours
		Inherent Availability	N/A
		Achieved Availability	N/A
		Operational Availability	N/A
	Spares	Spares/Repair Parts Demand Rate	N/A
		Spares/Repair Part Processing Time	Hours
		Probability of Spares Availability	N/A
		Probability of Success with Spares	N/A
Suitability	Usability	Initial Spares and Inventory Cost	USD
		Material Availability	N/A
		Software Availability	N/A
		Availability of Troubleshooting/Help	N/A

Top-Level "ility"	**Decomposed "ility"**	**Measurable Parameters**	**Units**
		Time Necessary for Post Processing	Hours
	Affordability	Personnel Training Cost	USD
		Distribution and Transportation Cost	USD
		Unscheduled Maintenance Cost	USD
		Component Cost	USD
		Material Cost per Pound	USD
		Consumable Cost Per 100hrs Operation	USD
Mobility and Human Systems Integration (HSI)	Environmental Conditions	Max Vibration Endurance	Hertz
		Average Operating Temperature	Celsius
		Max Operating Temperature	Celsius
		Min Operating Temperature	Celsius
		Maximum Operating Humidity	Percentage
	HSI/Mobility	Manpower Necessary to Operate	Number of Persons
		Operator Labor hours per Hour of System Operation	N/A
		Personnel Training Rate	Personnel Trained/ Hour
		Max System Length	Feet
		Max System Width	Feet
		Max System Height	Feet
		System Weight	Pounds (lbs.)
		Average System Operating Temperature	Celsius
		Maximum System Operating Temperature	Celsius

4. Code Structure

The Visual Basic for Applications (VBA) programming language was used to develop the code within Microsoft Excel. The AMPAT software consists of sections of VBA code, otherwise known as procedures; each procedure accomplishes different task. The two types of procedures within the code are functions (they perform an action and return a value), and subroutines or subs (they perform an action but do not return a value) (Alexander and Walkenbach 2019, 65).

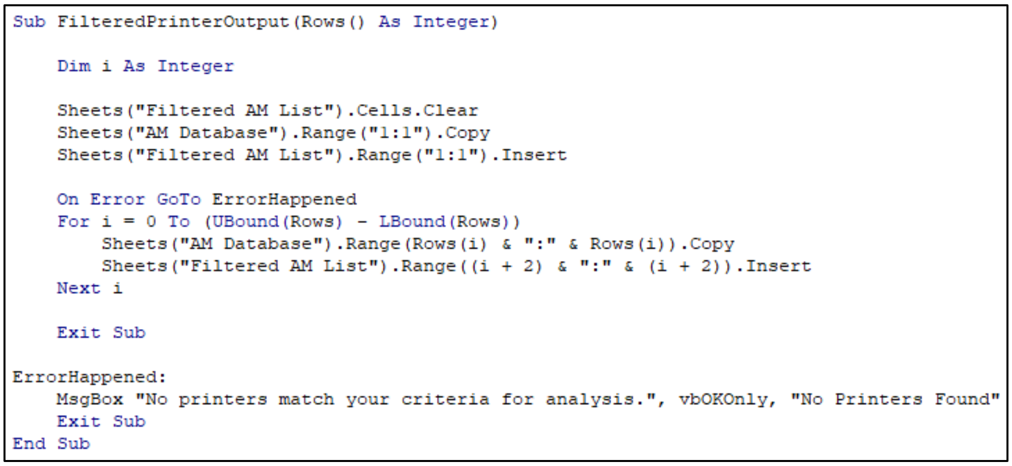
Figure 13 is an excerpt of the AMPAT code that demonstrates the use of a VBA function CheckBuildDimensions to return a result for the build dimensions of a specific AM technology. In this example, the function has three arguments (i.e., dimensions, CurrentStatus, and count) and a return type of Boolean. The function works by reading the AM Database for the build length, width, and height for each printer to decide if it meets the user-provided specifications. If the value being checked meets the specification, it is defined as ‘True’ and stored in a temporary array. If the value does not meet the user-defined specifications, it is defined as “False,” and the function ends. Once the function is defined, it can be called anywhere else in the code by simply using the function’s name and giving a value for each argument. The use of functions helped the NEAM team maintain modular software design; these groups of instructions can be called anywhere in the code, eliminating the need to write the same code repeatedly.



```
Function CheckBuildDimensions(dimensions() As Double, CurrentStatus As Boolean, count As Integer) As Boolean

    Dim temp As Boolean
    temp = CurrentStatus

    If Sheets("AM Database").Range("I" & (count + 1)) >= dimensions(0) Then
        temp = temp And True
    Else
        temp = temp And False
    End If

    If Sheets("AM Database").Range("J" & (count + 1)) >= dimensions(1) Then
        temp = temp And True
    Else
        temp = temp And False
    End If

    If Sheets("AM Database").Range("K" & (count + 1)) >= dimensions(2) Then
        temp = temp And True
    Else
        temp = temp And False
    End If

    CheckBuildDimensions = temp

End Function
```

Figure 13. Example of Function Used in AMPAT Software

Figure 14 is an excerpt of the AMPAT code that demonstrates the use of a VBA subroutine - FilteredPrinterOutput. This sub example has one argument (i.e., rows of type Integer). Unlike functions, subroutines perform a specific task but do not return a result or a value. Like functions, subroutines can be called anywhere else in the code by using the subroutine's name and giving a value for each argument. The sub shown in Figure 14 is used to clear the results from a previous user-entered selection analysis and insert the filtered AM system results from the current analysis. If no AM systems in the AM Database match the user-selected filtering criteria, a message will be displayed to the user stating that no AM systems match the analysis' selected criteria.



```
Sub FilteredPrinterOutput(Rows() As Integer)

    Dim i As Integer

    Sheets("Filtered AM List").Cells.Clear
    Sheets("AM Database").Range("1:1").Copy
    Sheets("Filtered AM List").Range("1:1").Insert

    On Error GoTo ErrorHappened
    For i = 0 To (UBound(Rows) - LBound(Rows))
        Sheets("AM Database").Range(Rows(i) & ":" & Rows(i)).Copy
        Sheets("Filtered AM List").Range((i + 2) & ":" & (i + 2)).Insert
    Next i

    Exit Sub

ErrorHappened:
    MsgBox "No printers match your criteria for analysis.", vbOKOnly, "No Printers Found"
    Exit Sub
End Sub
```

Figure 14. Example of Subroutine Used in AMPAT Software

B. ANALYSIS TOOL OVERVIEW AND CAPABILITIES

The NEAM team developed a Capability Taxonomy, otherwise known as a CV-2 model within the DOD Architecture Framework (DODAF), to demonstrate a hierarchy of the AMPAT capabilities. CV-2 models are structured with the most generic capabilities listed at the root of the hierarchy, while the leaves of the hierarchy provide more specific, detailed capabilities (Chief Information Officer [CIO] n.d.). As shown in Figure 15, the NEAM team identified four generic capabilities at the root of the CV-2 model: the capability to modify the AM system database, the capability to error check entries, the capability to perform AM system analysis, and the capability to view results. Each root is decomposed further to provide more specific details of the generic capabilities. The opaque boxes in Figure 15 represent capabilities that were developed to construct the MVP, the orange boxes represent capabilities that were developed using the agile sprint process, and the red boxes represent deferred capabilities that the NEAM team recognizes as important desired capabilities but was unable to develop due to time constraints.

The following sub-sections provide a top-level definition for each of the capabilities identified in the CV-2 and describe how each generic capability ties directly to the stakeholder needs and requirements analysis to develop a useful tool. Additional implementation details for each of the capabilities can be found in the AMPAT User Guide, which contains detailed descriptions of the tool functions, directions, and tutorials for how to use the tool.

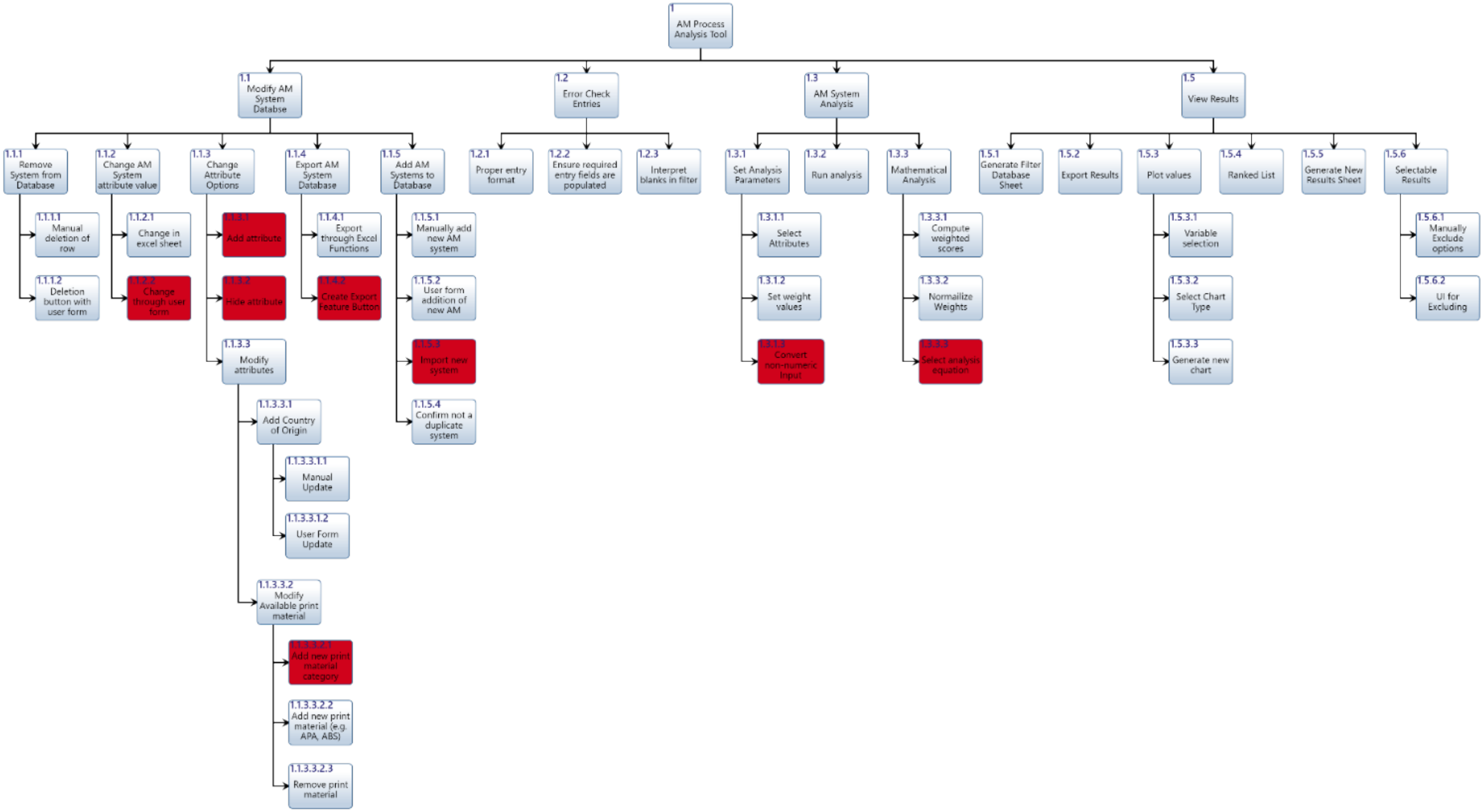


Figure 15. AMPAT CV-2 Model

1. Modify AM System Database

The first top-level capability of the AMPAT is modifying the AM system database. This capability is essential to satisfy database functionality requirement #4, as identified in Chapter III, Section G. The requirement states that the tool shall allow for the inclusion of an AM technology database to support expeditionary missions. Additionally, this capability also ties directly to tool functionality requirement #12, as identified in Chapter 3, Section G, and re-iterated here for convenience.

The tool shall allow for the user to add and modify the AM technology database in the following ways:

a. The tool shall allow manual additions and modifications of AM systems.

b. The tool shall automatically incorporate inputs into the AM technology database.

c. The tool shall automatically update the AM technology database without modification to the source code.

Figure 16 shows the decomposition of the top-level capability into five sub-components. The first is the ability for the user to manually remove systems from the database. The NEAM team planned an agile sprint to develop a deletion button within the tool using a user form. Additionally, the AMPAT tool allows the user to change AM system attribute values should the values change over time or an error must be rectified. Similar to the capability to remove systems, the user has the option of modifying the system attributes manually and the NEAM team used an agile sprint to develop a user form for this capability within the tool. The AMPAT also provides a limited capability for the user to modify certain attribute options including country of origin and print material. As shown in Figure 16, the AMPAT does not currently allow the users to add or hide attributes in the database without modifying the source code. While the NEAM team recognizes the benefit of this capability, it was determined to be of lower priority than the other features listed in the CV-2 and that it could not be implemented due to project time constraints. Similarly, the ability to import new AM systems into the database using a .txt, .csv, or other type of file could not be implemented due to time constraints; as a result, the user must manually add the new system to the database.

Another planned agile sprint was developing the functionality to export the AM system database by utilizing an export button that resides within the tool. Although the ability to export workbooks is an inherent function of the Excel software, the NEAM team determined that this user-friendly interface for exporting the AM system database may be of value to stakeholders to share system-specific data across multiple organizations to create a comprehensive and robust database.

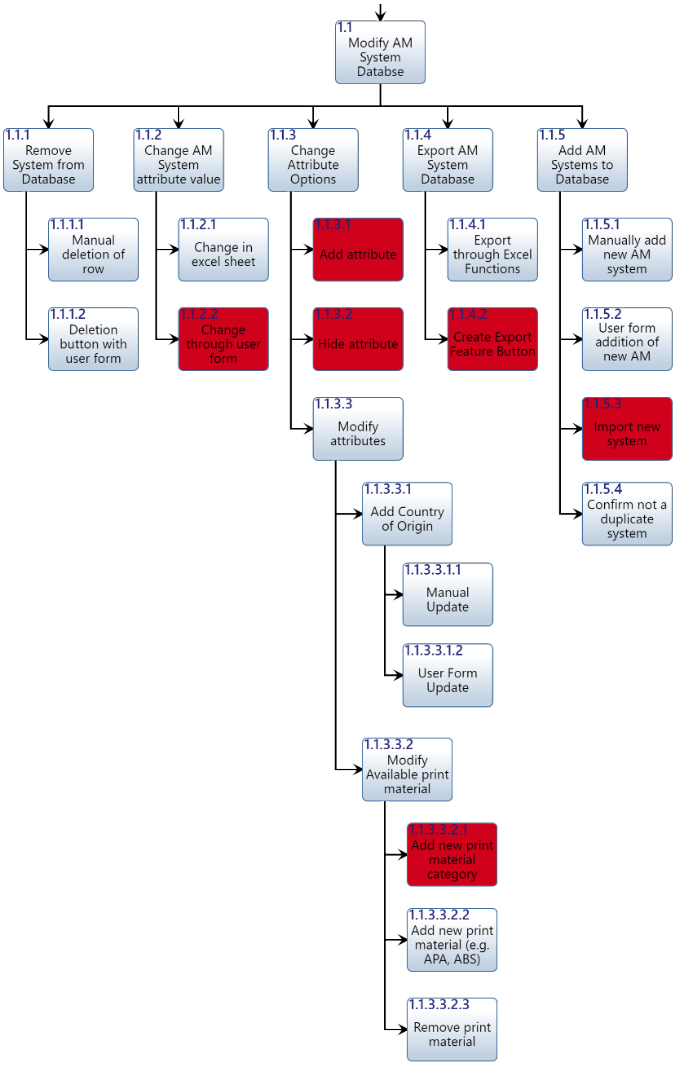


Figure 16. Modify AM System Database Capability

2. Error Check Entries

The second top-level capability of the AMPAT is error checking the user entries. This capability is critical to satisfy tool functionality requirement #13, as identified in Chapter III, Section G, and reiterated here for convenience.

The tool shall error check the database in the following ways:

a. Ensure input data is entered correctly (e.g., a letter listed instead of a number).

b. Ensure a duplication is not listed (e.g., multiple entries existing).

c. Ensure all required information for an entry is entered.

Figure 17 shows this top-level capability decomposed into three sub-components. The first sub-component is error checking to ensure that the entry is the proper format, which fulfills requirement #13a to ensure that input data is entered correctly. The second sub-component addresses requirement #13b by checking to ensure that all the required fields are populated. Next, the capability to check for blank entries will satisfy requirement #13c to ensure that all required information for an entry is entered.

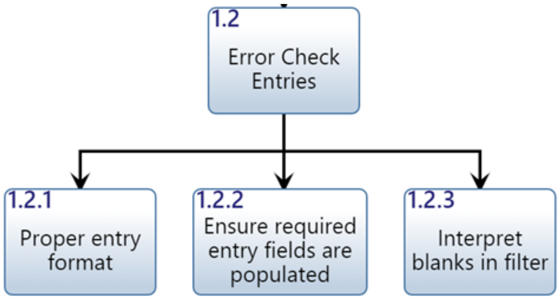


Figure 17. Error Check Entries Capability

3. Perform AM System Analysis

The third top-level capability of the AMPAT is performing the AM system analysis. This capability ties directly to top-level requirement #1 identified in Chapter 3, Section G, which states that the tool must provide stakeholders with the ability to analyze various AM systems for use in expeditionary environments including LOCE, EABO, and DMO.

Ultimately, this capability empowers the user to customize their analysis to address a specific use case or mission and help inform decisions of how best to employ AM capabilities throughout the fleet.

As shown in Figure 18, the AMPAT allows the user to first set the analysis parameters by identifying the specific attributes of interest (e.g., failure rate, operational availability, and/or other parameters listed in Table 2). Next, the AMPAT allows the user to set weighting values to each of the selected attributes to rank the importance of each attribute relative to one another. The user must set the weight values for the AMPAT to perform the mathematical analysis necessary to provide specific AM system recommendations. The mathematical analysis computes and normalizes the weighted scores of each AM system based upon the user weight inputs for each attribute.

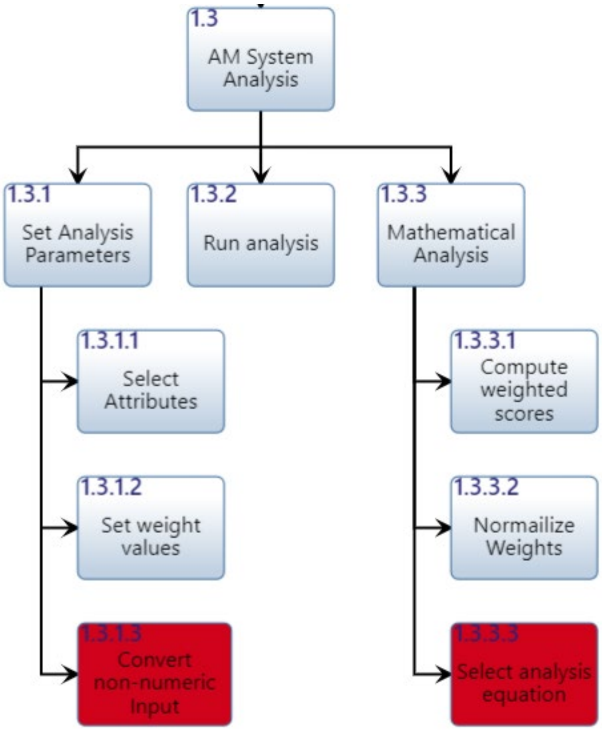


Figure 18. AM System Analysis Capability

The mathematical analysis equation used is based on normalizing all attribute values to the best value within the selection of AM systems. The best value within an attribute may be the largest value amongst the AM systems, such as the mean time between failure (MTBF), or conversely the best value may be the smallest value such as the mean downtime (MDT). To normalize these values, the top value,V_{Top}, is identified. If the largest value is the best value for an attribute, then equation 1 is used to normalize all AM system values for that attribute. Otherwise, if a smaller value is the best value for an attribute, equation 2 is used to normalize all the values under that particular attribute. Within the equations, i represents the AM system and j represents the attribute. Therefore V_{Top-j} is the best value amongst all selected AM systems for a specific attribute.

$$N_{ij} = {}^{V_{ij}}\!\big/_{V_{Top-j}} \tag{1}$$

$$N_{ij} = {}^{V_{Top-j}}\!\big/_{V_{ij}} \tag{2}$$

These normalized values are now unit less and range from$1 \geq N_{ij} > 0$. Note that 0 is an invalid value for all attributes. Now with all values being unitless and within the same range, they can be combined to generate an overall score for each AM system,S_i.

As discussed previously, the user will be able to define weights for the attributes as each attribute may not carry the same importance. These weights are normalized prior to their use in computing the overall score to ensure their summation equals 1.0 (or 100%). It is also important to note that only attributes selected for analysis will have their associated weights used within the weighting normalization process. The user defined weight for an attribute, w_j, is set by the user as a value between greater than 0 and equal or less than 100. The equation for the normalized weight, W_j, is described in equation 3.

$$W_j = {}^{w_j}\!\big/_{\sum w_j} \tag{3}$$

With the normalized values and the normalized weights, an AM system's effective attribute score can be computed by multiplying the AM system's normalized attribute value by the associated attributes' normalized weight. Summing these effective scores together for a single AM System will give that system's total score, S_i, as shown in equation 4.

$$S_i = \sum_{j=1}^{n} W_j \times N_{ij} \tag{4}$$

Ultimately, this is just a single method in which the NEAM team used to create an analysis score. Other methods were planned for an agile sprint to develop the functionality for AMPAT to allow the user to select the analysis equation to be used to rank the AM systems, but could not be implemented due to time constraints. Additional detail regarding the AMPAT mathematical analysis can be found the AMPAT user guide.

4. View Results

The last top-level capability of the AMPAT allows the user to view the results of the analysis. This capability satisfies top-level requirement #3 identified in Chapter III, Section G, which states that the tool shall provide an output to assist the user in the decision-making process. Figure 19 shows this top-level capability decomposed into several sub-components. Note that the sub-components in Figure 19 are not listed in any particular order and are not intended to represent a chronological sequence of events. As shown in the first sub-component, the AMPAT generates a filter database sheet that includes all the AM systems that satisfy the input parameters that were identified by the user prior to running the analysis. Additionally, the AMPAT provides a ranked list of those AM systems based upon the weighting values that were assigned to each parameter. Once the AM system results are displayed, the user can manually update it to exclude AM systems that are not of interest or are dominated by other options by removing the data in the sheet associated to those printers. The NEAM team planned an agile sprint that was geared towards developing a user interface that would allow the user to remove the AM systems that are dominated by other options but could not implement the functionality due to time constraints. The AMPAT User's Guide has information on how a user can manually remove dominated AM systems from the results. The AMPAT plots the results of the analysis by allowing the user to decide whether to plot by system or plot by attribute, as well as allow the user to choose the specific parameters to include in the plot. After the results are provided and plotted, the AMPAT allows the user to export the results using an export button within the tool.

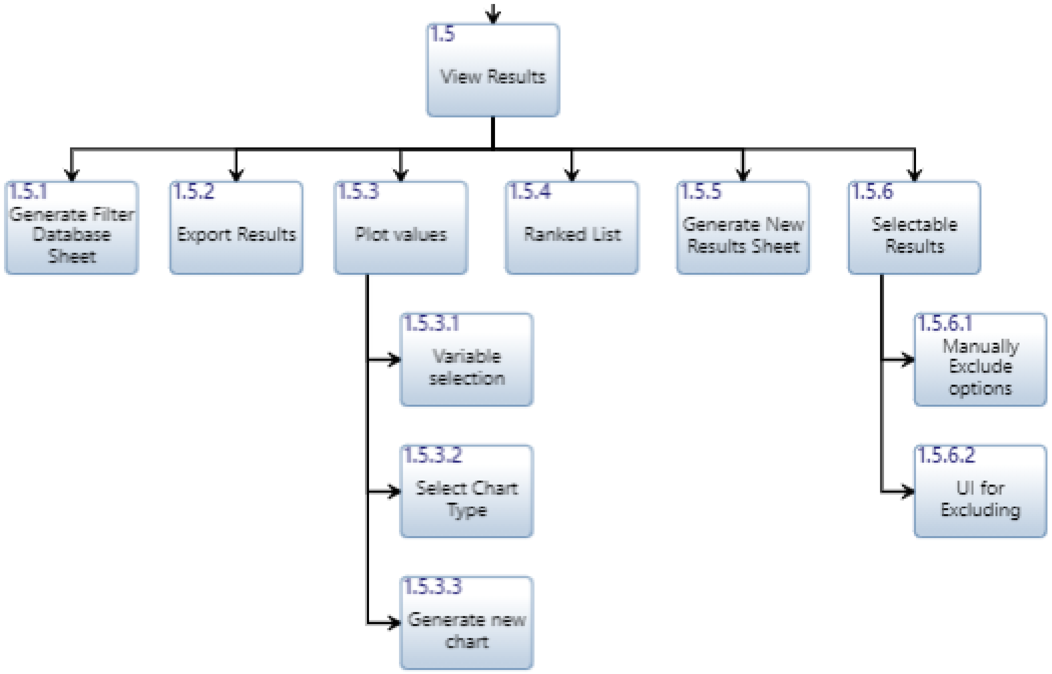


Figure 19. View Results Capability

C. LIMITATIONS

1. Inherent Limitations

AM systems capabilities is a rapidly developing landscape; every year there is a growth in new technology, improved functionality, and new systems become available in the market. While this presents great opportunities for the use of AM within the DON, it presents a challenge for the AMPAT. The AMPAT is dependent on a user-modifiable database and the available options within the database are limited to what is known and entered by the user. This puts an obligation on the decision maker to ensure the database has sufficient representation of the current AM options. A limited database can result in a limited decision analysis. Additionally, due to the nature of the project, the AMPAT was developed using open-source, unclassified information and therefore does not include detailed information regarding DOD-approved AM technologies within specific expeditionary units. If the user desires to conduct a more detailed analysis using classified information of AM systems and locations, the AMPAT must be up-domained to an appropriate security classification environment and the data must be entered manually.

That effort is estimated to be minimal, compared to the benefits that the tool provides to its users.

Further, the results of a decision analysis tool such as AMPAT are intended to aid the decision maker in making a well-informed decision. The tool outputs recommendations of specific AM technologies to be used based upon the provided inputs, but the decision maker should be wary that the recommendations are only as good as the input data provided. AMPAT is an asset the decision maker can use in combination with additional studies (e.g., cost analysis, feasibility and Analysis of Alternatives studies), to come to the most well-informed decision.

2. AMPAT Limitations

Specific to AMPAT, there are limitations on how the tool captures user input, functions, analyzes data, and outputs information. Most of the limitations can be tied to the restrictions of the scope of the project, namely the timeframe and resources available. The NEAM team captured potential future capabilities within the CV-2 in Figure 15 that could address numerous limitations in AMPAT.

The tool attempted to capture the most critical attributes that a decision maker would be interested in selecting an AM system for their mission needs. However, there are many more attributes that could be identified currently or could arise in the future. Additionally, there are certainly other attributes that a decision maker could be interested in related to their specific use case. Although the NEAM team attempted to minimize the necessity for modifying the source code, it is possible that users may need to modify the source code in the future to add attributes to AMPAT.

Throughout the tool development, the team researched and considered making the analysis an Excel Add-In. Making an Add-In would allow the tool to be available to a wider range of users because it would be able to be installed on any Excel workbook. Another benefit of creating an Excel Add-In is being able to password protect the code. However, because the tool is designed where each sheet has a specific purpose and structure, the Add-In would not be supported by any Excel workbook. Creating the Add-In would not populate the necessary sheet structure for the user to enter the AM system database and attribute information. Also, unlike purchasing COTS software programs, the AMPAT tool will include all passwords required to access the code and it is not proprietary. Future users are encouraged to study and alter the code as they see fit for their specific needs. Therefore, the password protection is not a significant benefit to the developers or the end users. Because of these reasons, the NEAM team decided not to create the Add-In capability.

AMPAT utilizes a single analysis method as discussed in Section B3 of this chapter, "Perform AM Analysis," which could be different than the desired analysis method of the decision maker. Other methods could be introduced in future developments of the tool to provide more flexibility and control to the decision maker, and could also complicate the design and usability of the tool. Additionally, the decision maker could desire to process the data through multiple analysis methods to compare results and identify consistencies and sensitivities.

3. Limitations from the Database

The strength of the decision process lies heavily on the breadth and quality of the AM system database. Conversely, this means that the database can limit the performance of the decision analysis. The analysis tool is limited to analyzing only systems that it has appropriate attribute information for. As there are hundreds of AM systems in existence, listing all systems is very cumbersome, if not impossible, due to the constant creation of new systems. Further, gathering the detailed attribute information is cumbersome as some of the information may not be readily available in system specification documents and must be derived from extensive research and use. The lack of information for an attribute can hinder that system from being adequately analyzed compared to others, resulting in it being excluded from the results or having a tainted score. As the database is built upon and used more over time, it will conceivably gain more AM systems and values for attributes.

The quality of an attribute value can also taint the score of an AM system. Not all attributes are objective values, such as training level and transportability. Also, some attribute values might be derived from multiple variables, making it hard to adequately compare. An example could be that a system may have a part quality attribute that is dependent upon the dimensions of the part. Another concern is that an attribute, such as print quality, could be dependent upon the user's ability or the part's design. A system that is easy to use may consistently develop medium quality parts, whereas a system requiring finesse could produce high quality parts for an expert user but could also be more apt to produce poor quality parts for a less skilled user. In addition, the part design could impact attributes, such as build time and quality. If an AM system utilizes support material, a part can take longer that has many overhang or cavity regions.

Lastly, the situational use of a system can affect the attribute values related to an AM system. Example attributes are print times based upon part design and dimensions, maintainability attributes dependent upon environment and use (and user upkeep), and component availability and logistic lead time based on the system use location. These attributes must be used with caution because they can be collected in different ways depending upon the specific mission or use case. An example of the variance in attribute values is the environment in which an AM system is used. When used in a well-maintained stationary facility the MTBF may be much longer than the system used in an outdoor environment where it is vulnerable to temperature swings, dust and debris, and being transported frequently.

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V. USE OF AMPAT IN THE DOD

This chapter provides several example use cases for the AMPAT and describes the operational environments for which the tool is intended to be used. An OV-1 is presented to visually present the operational scenarios that can be supported by AMPAT. Three specific scenarios are reviewed to demonstrate how the AMPAT tool can be used to conduct analysis and how the results are useful to expeditionary forces. Scenario A examines AM systems that could be deployed aboard an amphibious ship for large-scale missions. Scenario B examines the most suitable AM system to support a tailored mission with specific constraints on certain attributes. Scenario C walks through step-by-step instructions for how to use AMPAT to receive results to support a specific user-defined mission.

A. AMPAT USE CASES

The capabilities of the AMPAT depicted in the CV-2 model demonstrate the key features of the tool that were implemented to satisfy the project requirements. Figure 20 provides four examples of how the DOD can use the AMPAT and apply its capabilities to benefit the overall naval AM enterprise. For example, users can customize the AMPAT analysis to rank a set of AM printers with different specifications and characteristics to identify optimal AM system designs for warfighter needs in specific environments. Users from the NECC or other stakeholder organizations can also use the AMPAT to help inform investment decisions, such as determining which AM systems should be vetted through the qualification and certification process for use in the field throughout the fleet. Additionally, the AMPAT can be used to supplement the Advanced Manufacturing AoA that is currently being conducted by the Navy Expeditionary Combat Enterprise to evaluate alternative options for expeditionary AM capabilities that will ultimately influence DOD AM requirements and investment decisions.

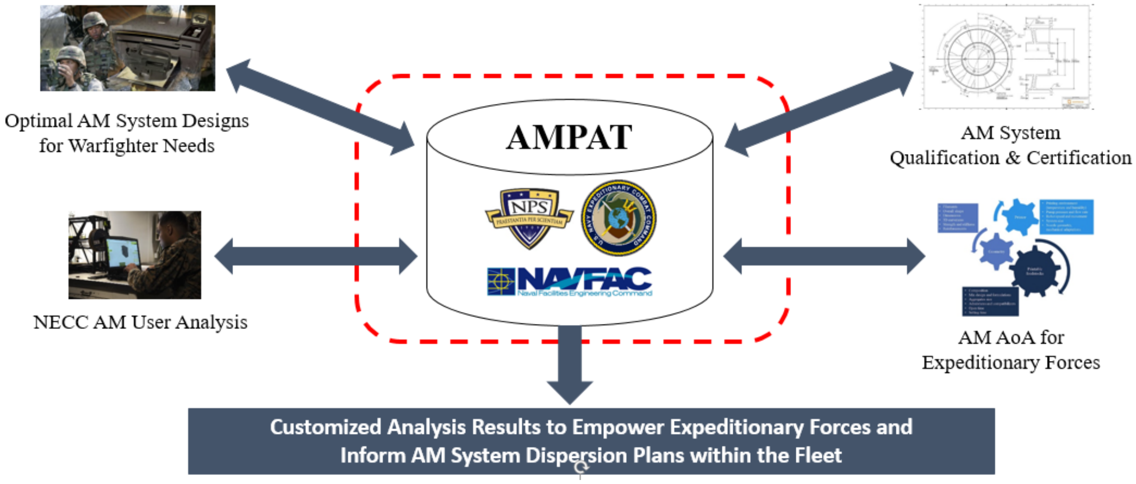


Figure 20. AMPAT Context Diagram. Adapted from Naval Postgraduate School (2017).

This analysis process will assist the NECC in identifying the best AM system for a specific mission and use case; the AM use cases of interest include the generation of spare and repair parts. Existing example use cases include the fabrication of structural components for the Nibbler drone, replacement handles for the high mobility multipurpose wheeled vehicle (HMMWV), and snowshoe clips (Friedell and Audette 2018). Readily available open-source, unclassified AM system data was used to populate the AMPAT; specifically, the team focused on systems that could potentially be used in locations such as FOBs and ANBs. Users can add to or modify the AMPAT database to include DOD approved AM systems as they become available.

B. OPERATIONAL SCENARIO OVERVIEW

An OV-1 of AM capabilities supporting expeditionary operations is depicted in Figure 21. The figure shows how the AMPAT software can assist in selecting AM systems that directly support the specific expeditionary environment and end-use of the AM components. Figure 21 demonstrates that AM systems can be located anywhere from onboard ships to inside tactical vehicles. The OV-1 also shows how the parts that are printed from these systems can be used for many applications such as repairing vehicles or unmanned platforms or replacing components in the field to deployed troops.

Prior to the procurement and deployment of an AM system, the decision maker can utilize the AMPAT to guide them in selecting the AM system that best meets their mission needs and capability gaps. The AMPAT software is structured to allow the decision maker to focus on the use of the AM system in terms of mission constraints (e.g., size, weight, and power (SWaP)), AM part characteristics, and logistics (e.g., current systems in use, MTBF, and cost). Examples of these systems are depicted by the orange triangles in the OV-1. It is important to note that each system does not need to be the same, as their operational use and environment could be different. These systems can be used at different locations, including aboard a ship for building a supply of parts prior to an amphibious breach, in an FOB or ANB for building spare parts, or on a ground assault vehicle for building repair parts. Further, these AM systems could be used at an FOB as part of a manufacturing capability such as EXMAN.

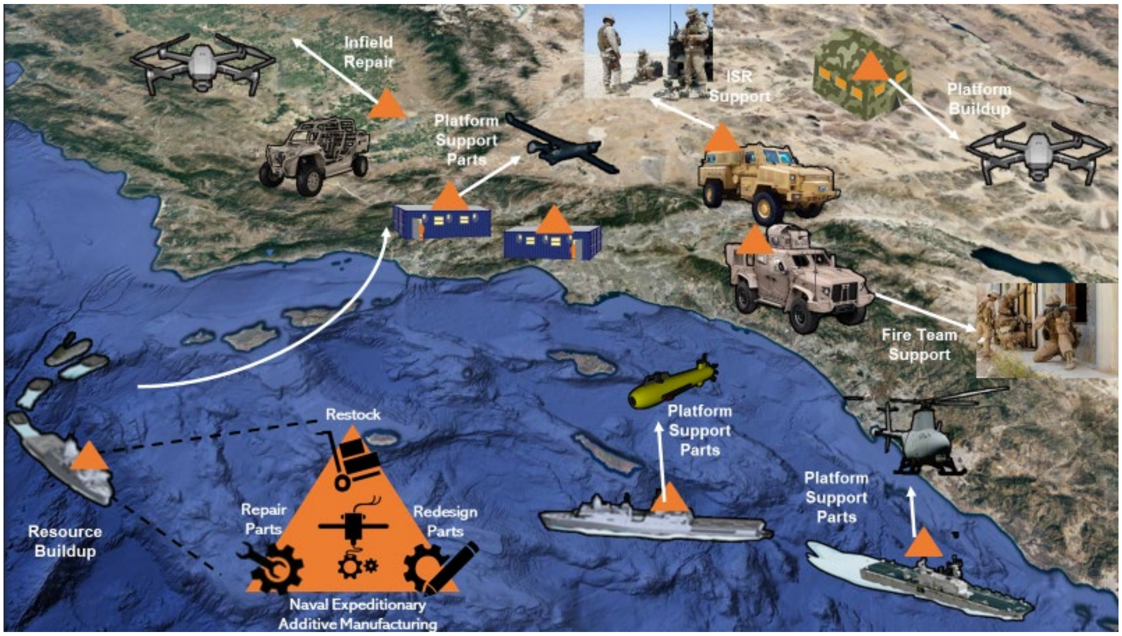


Figure 21. OV-1 of NEAM, Demonstrating Deployed AM Assets to Support Expeditionary Operations

The use of these systems includes fabricating spare parts as needed or in advance of a mission to ensure there is a well-stocked supply to send with departing forces. Additionally, warfighters are continually provided with new tools and systems to use; as the number of deployed systems increase, keeping well-stocked and correctly configured replacement parts becomes more difficult. AM can address this issue by producing parts on-demand, which significantly reduces the lead time required to support the fleet. There are even unmanned systems (e.g., Nibbler) where all structural components are designed to be built with AM parts. Lastly, a curated AM system can have a major effect on ensuring the warfighter has properly functioning gear and necessary tools. This can include simple things such as lids on containers, mounts and covers for sensors, rails for sliding doors, or even clips for gear. These small components can assist the warfighter in maintaining functioning equipment and focus on the objectives at hand.

C. EXAMPLE SCENARIOS

This section defines three different mission needs for which the AMPAT can identify an appropriate AM system. Scenarios A and B provide generic examples of missions that could be supported by AMPAT analysis. Scenario A examines AM systems that could be deployed aboard an amphibious ship for large-scale missions. Scenario B examines the most suitable AM system to support a tailored mission with specific constraints on certain attributes such as print time related to using an AM system for a single specific system. Scenario C provides a deep dive into a scenario that requires an AM system to produce replacement parts for an FOB. Scenario C walks through step-by-step instructions for how to use AMPAT to receive results to support a specific user-defined mission. With these missions, environments, and requirements in mind, this section will step through the analysis process the decision maker will go through to use the AMPAT tool in assisting them in their decision.

1. Scenario A

In Scenario A, AM systems are desired onboard an amphibious class ship, to fabricate an array of parts in preparation for an amphibious landing and support onshore missions. The systems will need to support multiple material types, create reliable products, and operate for great lengths of time, as once the missions are defined, a vast number of parts will be required. Given that these systems will be utilized on a ship as part of a fabrication lab, the SWaP of the systems will be considered by the decision makers, but are not the highest criteria. Additionally, there is expected to be support of a knowledgeable and well-equipped maintenance and operator team. The decision maker specifies that there is a need to use multiple materials and that part quality and reliability are the most important system characteristics. Because these systems will be integrated within the network on the ship, security is a major factor. To start, the users set filters such as country of origin, pre-approved and undecided systems, and minimum resolution settings to eliminate systems from their large database and exclude materials that they are not interested in (i.e., ceramic and concrete).

Once the filter parameters are set, the user can set up the parameters for the preliminary weighted analysis, which will only be conducted on the systems that meet the filter criteria. The preliminary analysis will allow the user to understand the available AM systems options based upon the input criteria. The user can then refine the analysis by selecting attributes that focus on quality, reliability, and other known measures of the system that they are interested in. Though SWaP are not the most important attributes for their specific analysis, they can include those parameters in the analysis and assign a low weighting score to aid their decision if desired.

After running this analysis, the decision maker will have weighted scores for the filtered AM systems. The decision maker can identify which AM systems dominate others and begin eliminating the inferior systems by plotting the resulting scores vs. different attributes. This will allow the decision maker to develop a smaller, tailored list that meets the decision makers needs and spans various material options. This manageable list of systems will allow the decision maker to investigate other attributes more thoroughly, such as availability and mobility. The decision maker will use the curated list to conduct further analysis based on the new attribute data. Using this process, the decision maker will continue to identify the best AM solutions and limit the number of systems to investigate.

2. Scenario B

While Scenario A focused on a large-scale AM solution, Scenario B looks at a more focused and specific need. In this scenario, a decision maker is looking for a system that can accompany a small team in the field on missions to support fabrication and replacement parts for a UAV. This UAV is designed to utilize 3D printed structural parts that are well defined. The UAV is viewed as expendable and does not require components to have a long lifetime. However, the parts will undergo high stress and strain, and require non-catastrophic failure. For this mission, it is specified that a particular material should be used (e.g., carbon fiber filled nylon). Additionally, as this AM system is desired to be used in active missions, it has some other tight constraints, including SWaP, print resolution, and print speed. Further, the required print dimensions are defined.

Based on the mission needs and the printed part requirements, the decision maker sets a filter based on the specific material required, along with parameters related to print resolution and print speed. The user then sets the analysis weights related to the size, and weight (i.e., system mass); where the size of the system is viewed as very important and the weight is mildly important as long as it meets a threshold that can be set in the filter. The AMPAT completes the assessment and presents results within a concise graph and list format.

From this analysis, the decision maker can quickly understand what systems present the best options related to print speed and SWaP. The decision maker may be flexible with some attributes and decide not to factor them into the analysis, such as the system's approval status, country of origin, and cost. For example, if a system that is not approved or from a foreign country is found to be profoundly superior to alternative options, it may be acceptable to use if security measures are put in place to ensure the integrity of the parts and the safety of the user. Similarly, a high-cost system may have the highest-ranked score overall, and the decision maker may decide to purchase a few systems to test reliability, availability, and sustainability attributes to decide if the high cost is acceptable.

Further, other attributes related to usability may be important to support this mission. Within this mission, there will be a much broader group of users; therefore, ease of use, level of training, and infield maintainability would be attributes that are valuable to investigate further on a select few systems. With this new information, AMPAT can run another weighted analysis to identify the ideal system. Additionally, this analysis could exclude previous attributes or adjust the weighting to understand the new attributes better.

Scenarios A and B both demonstrate how decision makers could use AMPAT to conduct analysis for specific use cases and mission needs, as these scenarios follow the process of ranking the attributes for the mission, performing a down-selection of the AM systems based on acceptable characteristics, performing a baseline analysis, conducting further detailed research into attributes, and performing refined analysis. Through this process, the attribute information of AM systems continues to improve and become more well-defined; in turn, defining more attributes will allow the AMPAT to make more informed calculations.

3. Scenario C

This last example examines a support function in the expeditionary environment. This example provides a detailed sample run-through of the software, which explains how a user can utilize the functions of the tool that are shown on the dashboard in Figure 22. While this section will highlight many key steps and processes, a thorough review of the tool functionality can be found in the User's Guide. This example utilizes a combination of AM system technical specifications gathered from the manufacturer and example values to aide in the demonstration. The desired AM system(s) for this mission are to be utilized to produce replacement parts and provide restock of supplies at an FOB.

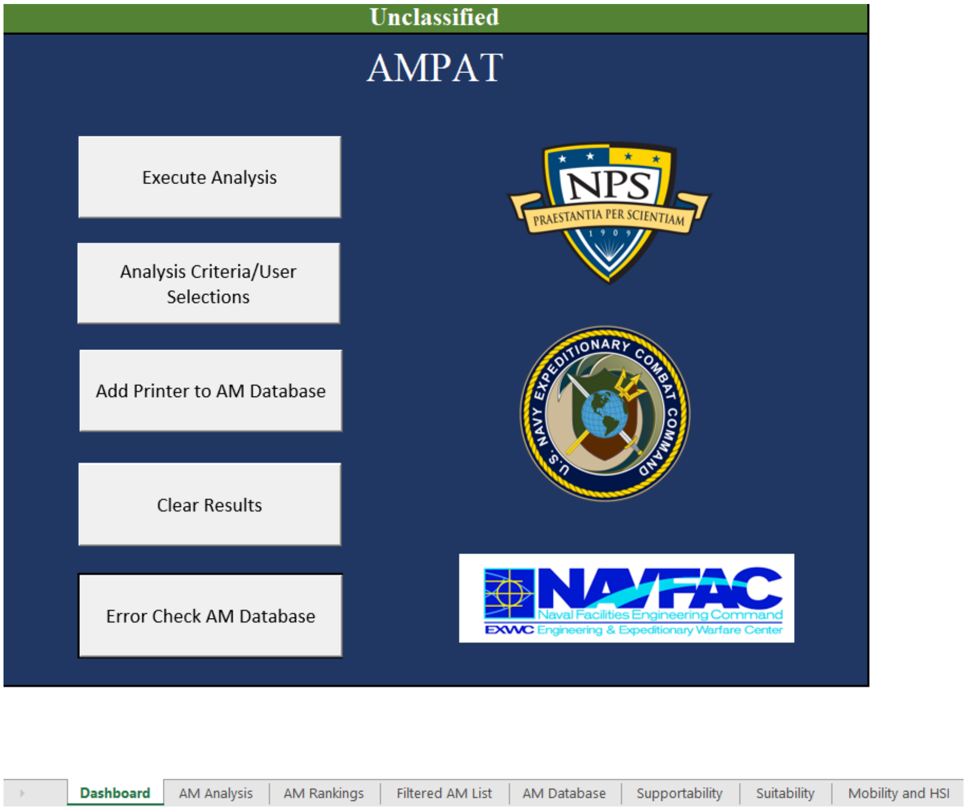
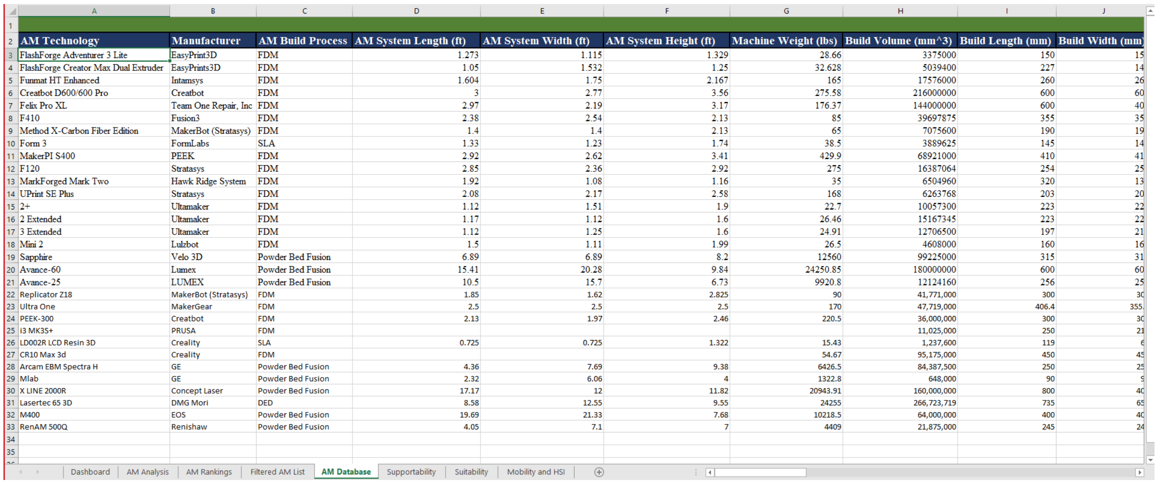


Figure 22. AMPAT Dashboard

These bases act as a hub for a wide range of missions, platforms, and systems. The decision maker prefers a range of polymer print material options, as there are a variety of parts to be fabricated in support of the many operations conducted within the base. It is important that these systems have a high reliability value. In order to support high reliability, the system(s) must have a large MTBF and a short MDT. Further, because the AM system(s) will be utilized at an FOB, resources must be wisely managed, and the logistics of transportation must be considered. These criteria will have a direct impact on the size, weight, and power of the AM system(s).

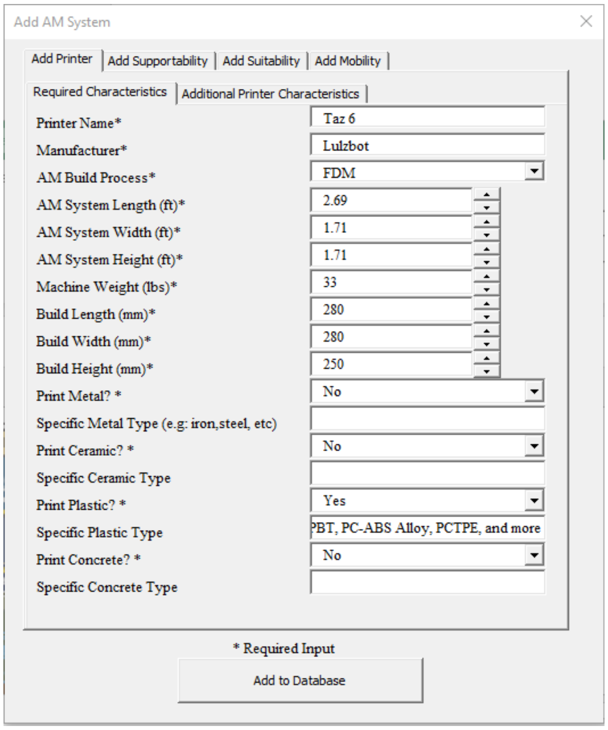
The first step of the process is to conduct a survey of the AM systems currently within the AM database and to perform market research on available systems to be added to the AM systems database. The purpose of this step is to add AM system information to fulfill the required attributes of the AMPAT and to capture readily available attributes that are desired for the mission. A current database with a partial view of the attributes is shown in Figure 23.



AM Technology	Manufacturer	AM Build Process	AM System Length (ft)	AM System Width (ft)	AM System Height (ft)	Machine Weight (lbs)	Build Volume (mm^3)	Build Length (mm)	Build Width (mm
FlashForge Adventurer 3 Lite	EasyPrint3D	FDM	1.273	1.115	1.329	28.66	3375000	150	15
FlashForge Creator Max Dual Extruder	EasyPrints3D	FDM	1.05	1.532	1.25	32.628	5039400	227	14
Funmat HT Enhanced	Intamsys	FDM	1.604	1.75	2.167	165	17576000	260	26
Creatbot D600/600 Pro	Creatbot	FDM	3	2.77	3.56	275.58	216000000	600	60
Felix Pro XL	Team One Repair, Inc	FDM	2.97	2.19	3.17	176.37	144000000	600	40
F410	Fusion3	FDM	2.38	2.54	2.13	85	39697875	355	35
Method X-Carbon Fiber Edition	MakerBot (Stratasys)	FDM	1.4	1.4	2.13	65	7075600	190	19
Form 3	FormLabs	SLA	1.33	1.23	1.74	38.5	3889625	145	14
MakerPI S400	PEEK	FDM	2.92	2.62	3.41	429.9	68921000	410	41
F120	Stratasys	FDM	2.85	2.36	2.92	275	16387064	254	25
MarkForged Mark Two	Hawk Ridge System	FDM	1.92	1.08	1.16	35	6504960	320	13
UPrint SE Plus	Stratasys	FDM	2.08	2.17	2.58	168	6263768	203	20
2+	Ultamaker	FDM	1.12	1.51	1.9	22.7	10057300	223	22
2 Extended	Ultamaker	FDM	1.17	1.12	1.6	26.46	15167345	223	22
3 Extended	Ultamaker	FDM	1.12	1.25	1.6	24.91	12706500	197	21
Mini 2	Lulzbot	FDM	1.5	1.11	1.99	26.5	4608000	160	16
Sapphire	Velo 3D	Powder Bed Fusion	6.89	6.89	8.2	12560	99225000	315	31
Avance-60	Lumex	Powder Bed Fusion	15.41	20.28	9.84	24250.85	180000000	600	60
Avance-25	LUMEX	Powder Bed Fusion	10.5	15.7	6.73	9920.8	12124160	256	25
Replicator Z18	MakerBot (Stratasys)	FDM	1.85	1.62	2.825	90	41,771,000	300	30
Ultra One	MakerGear	FDM	2.5	2.5	2.5	170	47,719,000	406.4	355.
PEEK-300	Creatbot	FDM	2.13	1.97	2.46	220.5	36,000,000	300	30
i3 MK3S+	PRUSA	FDM					11,025,000	250	21
LD002R LCD Resin 3D	Creality	SLA	0.725	0.725	1.322	15.43	1,237,600	119	6
CR10 Max 3d	Creality	FDM				54.67	95,175,000	450	45
Arcam EBM Spectra H	GE	Powder Bed Fusion	4.36	7.69	9.38	6426.5	84,387,500	250	25
Mlab	GE	Powder Bed Fusion	2.32	6.06	4	1322.8	648,000	90	9
X LINE 2000R	Concept Laser	Powder Bed Fusion	17.17	12	11.82	20943.91	160,000,000	800	40
Lasertec 65 3D	DMG Mori	DED	8.58	12.55	9.55	24255	266,723,719	735	65
M400	EOS	Powder Bed Fusion	19.69	21.33	7.68	10218.5	64,000,000	400	40
RenAM 500Q	Renishaw	Powder Bed Fusion	4.05	7.1	7	4409	21,875,000	245	24

Figure 23. Sample Database of Various AM Systems

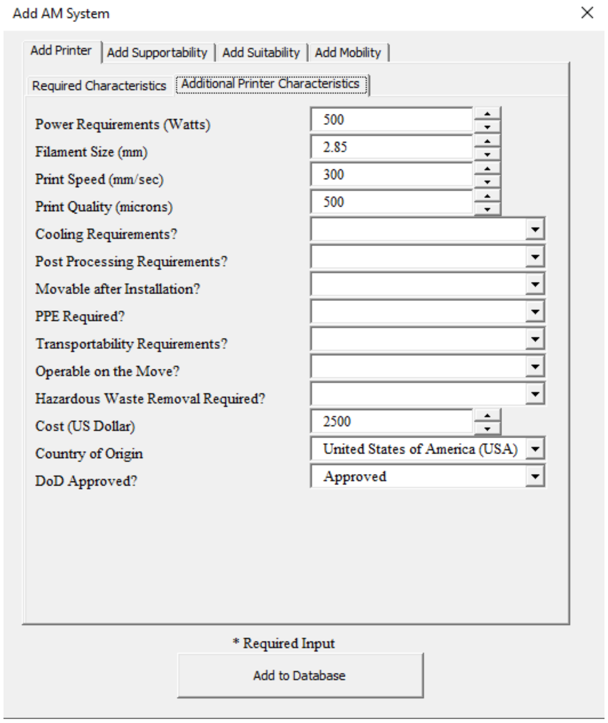
The user knows of an additional AM system, the TAZ 6 by Lulzbot, through its use in other commands and decides to enter it into the database for consideration. The user will select the *Add Printer to AM Database* button on the *Dashboard* tab. This action will pop-up the user form to allow the user to enter in attribute values for the system. The values for the TAZ 6 system come from the specification sheet provided by the manufacturer (Lulzbot 2018). Using this specification sheet, the required information, along with additional values, are entered in the user form as shown in Figure 24, Figure 25, Figure 26, and Figure 27.



Printer Name*	Taz 6
Manufacturer*	Lulzbot
AM Build Process*	FDM
AM System Length (ft)*	2.69
AM System Width (ft)*	1.71
AM System Height (ft)*	1.71
Machine Weight (lbs)*	33
Build Length (mm)*	280
Build Width (mm)*	280
Build Height (mm)*	250
Print Metal? *	No
Specific Metal Type (e.g: iron,steel, etc)	
Print Ceramic? *	No
Specific Ceramic Type	
Print Plastic? *	Yes
Specific Plastic Type	PBT, PC-ABS Alloy, PCTPE, and more
Print Concrete? *	No
Specific Concrete Type	

* Required Input

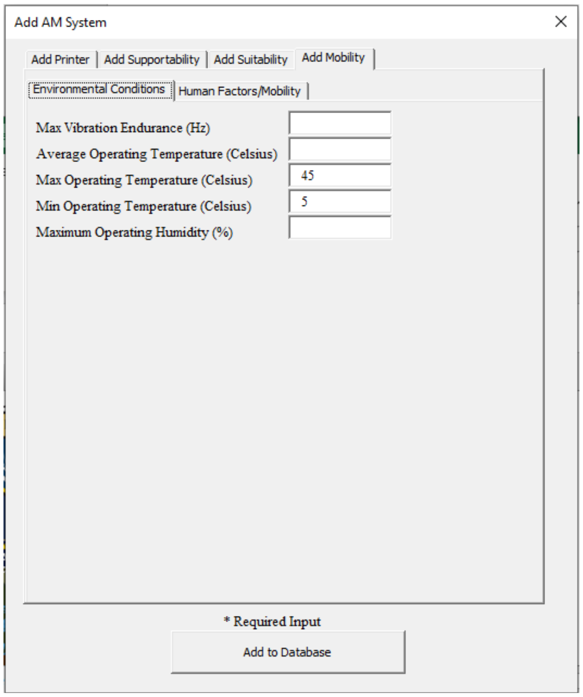
Figure 24. Adding Required Attributes for the TAZ 6 3D Printer



Power Requirements (Watts)	500
Filament Size (mm)	2.85
Print Speed (mm/sec)	300
Print Quality (microns)	500
Cooling Requirements?	
Post Processing Requirements?	
Movable after Installation?	
PPE Required?	
Transportability Requirements?	
Operable on the Move?	
Hazardous Waste Removal Required?	
Cost (US Dollar)	2500
Country of Origin	United States of America (USA)
DoD Approved?	Approved

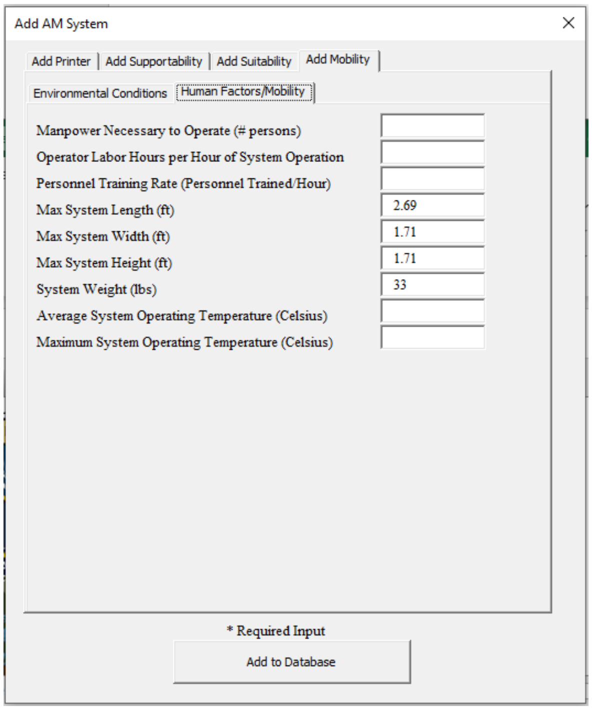
* Required Input

Figure 25. Adding Additional Printer Characteristics for the TAZ 6 3D Printer



Max Vibration Endurance (Hz)
Average Operating Temperature (Celsius)
Max Operating Temperature (Celsius) 45
Min Operating Temperature (Celsius) 5
Maximum Operating Humidity (%)

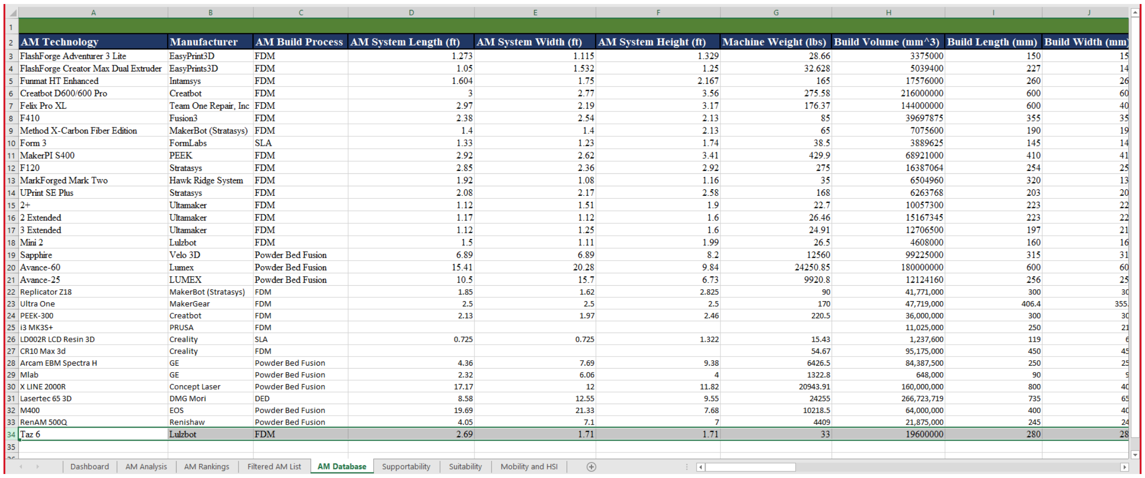
Figure 26. Adding Environmental Conditions Information for the TAZ 6 3D Printer



Manpower Necessary to Operate (# persons)
Operator Labor Hours per Hour of System Operation
Personnel Training Rate (Personnel Trained/Hour)
Max System Length (ft) 2.69
Max System Width (ft) 1.71
Max System Height (ft) 1.71
System Weight (lbs) 33
Average System Operating Temperature (Celsius)
Maximum System Operating Temperature (Celsius)

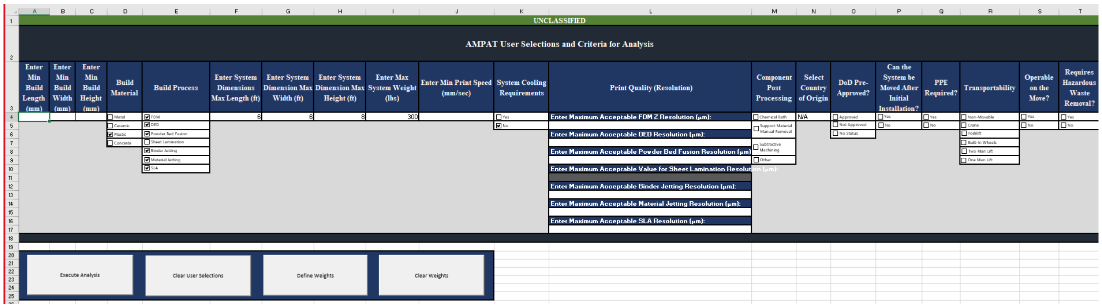
Figure 27. Adding Human Factors and Mobility Information for the TAZ 6 3D Printer

After the database is updated with the additional system, shown in Figure 28, there are now 32 AM systems in the database and the user wants to proceed to the analysis process. The next step is to create the filter criteria, which will constrain the weighted analysis to only AM systems that meet mission requirements. This is done by selecting the *AM Analysis* tab. From here, initial filter criteria such as the process type, size, material type, and cooling requirements are set. These preferences are shown in Figure 29.



AM Technology	Manufacturer	AM Build Process	AM System Length (ft)	AM System Width (ft)	AM System Height (ft)	Machine Weight (lbs)	Build Volume (mm^3)	Build Length (mm)	Build Width (mm)
FlashForge Adventurer 3 Lite	EasyPrint3D	FDM	1.273	1.115	1.329	28.66	3375000	150	15
FlashForge Creator Max Dual Extruder	EasyPrints3D	FDM	1.05	1.532	1.25	32.628	5039400	227	14
Funmat HT Enhanced	Intamsys	FDM	1.604	1.75	2.167	165	17576000	260	26
Creatbot D600/600 Pro	Creatbot	FDM	3	2.77	3.56	275.58	216000000	600	60
Felix Pro XL	Team One Repair, Inc	FDM	2.97	2.19	3.17	176.37	144000000	600	40
F410	Fusion3	FDM	2.38	2.54	2.13	85	39697875	355	35
Method X-Carbon Fiber Edition	MakerBot (Stratasys)	FDM	1.4	1.4	2.13	65	7075600	190	19
Form 3	FormLabs	SLA	1.33	1.23	1.74	38.5	3889625	145	14
MakerPI S400	PEEK	FDM	2.92	2.62	3.41	429.9	68921000	410	41
F120	Stratasys	FDM	2.85	2.36	2.92	275	16387064	254	25
MarkForged Mark Two	Hawk Ridge System	FDM	1.92	1.08	1.16	35	6504960	320	13
UPrint SE Plus	Stratasys	FDM	2.08	2.17	2.58	168	6263768	203	20
2+	Ultamaker	FDM	1.12	1.51	1.9	22.7	10057300	223	22
2 Extended	Ultamaker	FDM	1.17	1.12	1.6	26.46	15167345	223	22
3 Extended	Ultamaker	FDM	1.12	1.25	1.6	24.91	12706500	197	21
Mini 2	Lulzbot	FDM	1.5	1.11	1.99	26.5	4608000	160	16
Sapphire	Velo 3D	Powder Bed Fusion	6.89	6.89	8.2	12560	99225000	315	31
Avance-60	Lumex	Powder Bed Fusion	15.41	20.28	9.84	24250.85	180000000	600	60
Avance-25	LUMEX	Powder Bed Fusion	10.5	15.7	6.73	9920.8	12124160	256	25
Replicator Z18	MakerBot (Stratasys)	FDM	1.85	1.62	2.825	90	41,771,000	300	30
Ultra One	MakerGear	FDM	2.5	2.5	2.5	170	47,719,000	406.4	355.
PEEK-300	Creatbot	FDM	2.13	1.97	2.46	220.5	36,000,000	300	30
i3 MK3S+	PRUSA	FDM					11,025,000	250	21
LD002R LCD Resin 3D	Creality	SLA	0.725	0.725	1.322	15.43	1,237,600	119	6
CR10 Max 3d	Creality	FDM				54.67	95,175,000	450	45
Arcam EBM Spectra H	GE	Powder Bed Fusion	4.36	7.69	9.38	6426.5	84,387,500	250	25
Mlab	GE	Powder Bed Fusion	2.32	6.06	4	1322.8	648,000	90	9
X LINE 2000R	Concept Laser	Powder Bed Fusion	17.17	12	11.82	20943.91	160,000,000	800	40
Lasertec 65 3D	DMG Mori	DED	8.58	12.55	9.55	24255	266,723,719	735	65
M400	EOS	Powder Bed Fusion	19.69	21.33	7.68	10218.5	64,000,000	400	40
RenAM 500Q	Renishaw	Powder Bed Fusion	4.05	7.1	7	4409	21,875,000	245	24
Taz 6	Lulzbot	FDM	2.69	1.71	1.71	33	19600000	280	28

Figure 28. AM Database with new AM system, TAZ 6



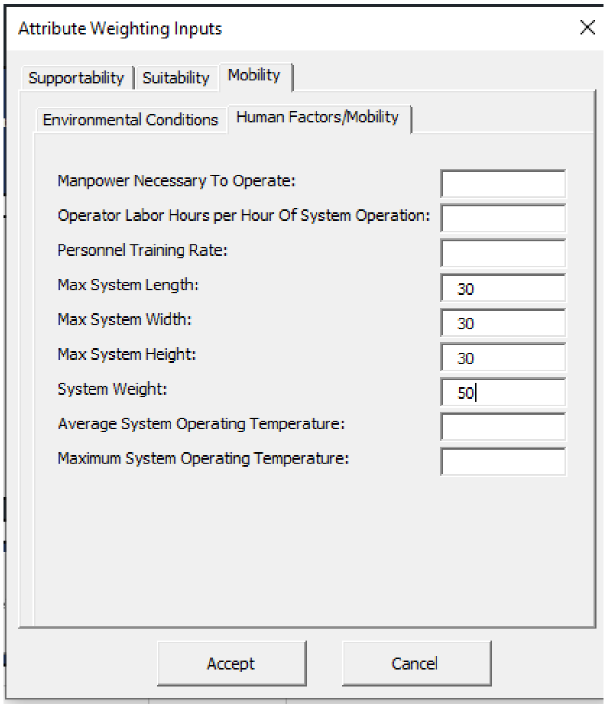
UNCLASSIFIED

AMPAT User Selections and Criteria for Analysis

Enter Min Build Length (mm):
Enter Min Build Width (mm):
Enter Min Build Height (mm):
Build Material: ☐ Metal ☐ Ceramic ☑ Plastic ☐ Concrete
Build Process: ☑ FDM ☑ DED ☑ Powder Bed Fusion ☐ Sheet Lamination ☑ Binder Jetting ☑ Material Jetting ☑ SLA
Enter System Dimensions Max Length (ft): 6
Enter System Dimension Max Width (ft): 6
Enter System Dimension Max Height (ft): 8
Enter Max System Weight (lbs): 300
Enter Min Print Speed (mm/sec):
System Cooling Requirements: ☐ Yes ☑ No
Print Quality (Resolution):
Enter Maximum Acceptable FDM Z Resolution (μm):
Enter Maximum Acceptable DED Resolution (μm):
Enter Maximum Acceptable Powder Bed Fusion Resolution (μm)
Enter Maximum Acceptable Value for Sheet Lamination Resolution (μm):
Enter Maximum Acceptable Binder Jetting Resolution (μm):
Enter Maximum Acceptable Material Jetting Resolution (μm):
Enter Maximum Acceptable SLA Resolution (μm):
Component Post Processing: ☐ Chemical Bath ☐ Support Material Manual Removal ☐ Subtractive Machining ☐ Other
Select Country of Origin: N/A
DoD Pre-Approved?: ☐ Approved ☐ Not Approved ☐ No Status
Can the System be Moved After Initial Installation?: ☐ Yes ☐ No
PPE Required?: ☐ Yes ☐ No
Transportability: ☐ Non-Movable ☐ Crane ☐ Forklift ☐ Built-In Wheels ☐ Two Man Lift ☐ One Man Lift
Operable on the Move?: ☐ Yes ☐ No
Requires Hazardous Waste Removal?: ☐ Yes ☐ No

Figure 29. Initial Filter Criteria for AM Analysis

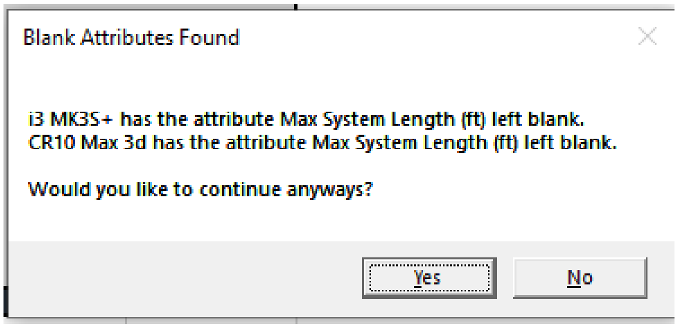
Now that the filter criteria are set, the next step is to enter the weights for the desired attributes. Preliminary results from this analysis will help the user find the most applicable AM technology for the given scenario. If the attribute analysis parameters are not fully defined for each AM system, then unintentional filtering and rankings may result due to lack of information. However, the tool will alert the user to populate the necessary information or ask if they would like to continue with the analysis. For this scenario, the initial attributes will be the size and weight of the AM systems. The weights for the attributes can range between 0 and 100. In this scenario, weight is more important than size and is assigned a higher number, as shown in Figure 30.



Manpower Necessary To Operate:
Operator Labor Hours per Hour Of System Operation:
Personnel Training Rate:
Max System Length: 30
Max System Width: 30
Max System Height: 30
System Weight: 50
Average System Operating Temperature:
Maximum System Operating Temperature:

Figure 30. Attribute Weighting Inputs

Once the filter and weighting criteria are set, the analysis can be run by pressing the *Execute Analysis* button on the *Dashboard* tab, or by clicking the *Execute Analysis* button on the *AM Analysis* tab. This will populate the filtered AM Database tab and the Analysis Results tab. However, prior to executing the analysis, this example scenario produces a pop-up message as shown in Figure 31, indicating that some attribute values are missing for a couple AM systems. First, the user will examine the effects of these missing values on the analysis results. Afterwards, the user will manually enter the attribute values and re-run the analysis to observe the new results.

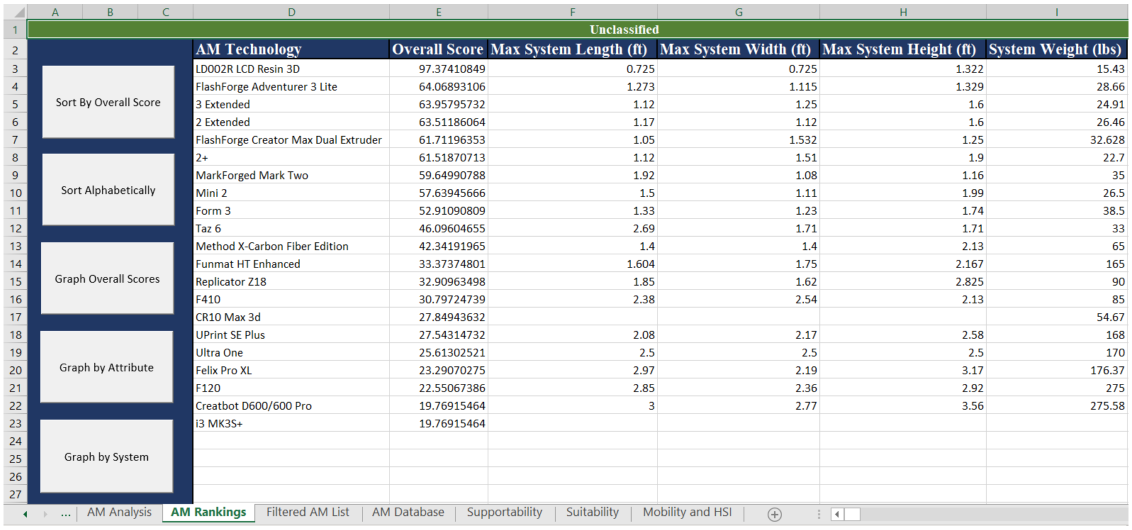

Blank Attributes Found

i3 MK3S+ has the attribute Max System Length (ft) left blank.
CR10 Max 3d has the attribute Max System Length (ft) left blank.

Would you like to continue anyways?

Figure 31. Pop-up Message Indicating Missing Attribute Values

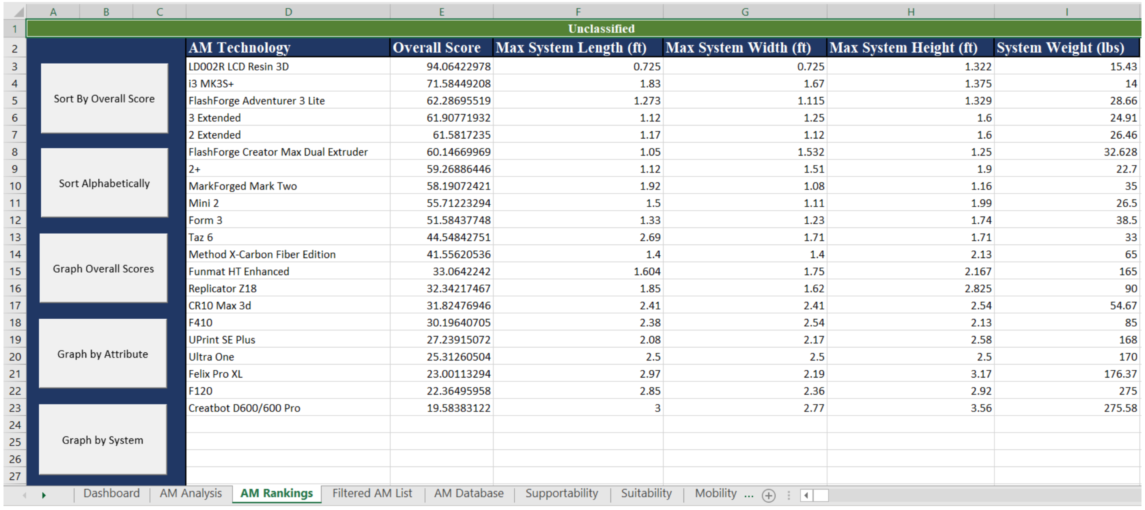
The results of the analysis appear in the *AM Rankings* tab, which for this example can be seen in Figure 32. These results are organized by the overall score using the buttons on the left of the page. The first aspect to note is that through the filtering process, the AMPAT has down-selected 21 AM systems out of the 32 AM systems in the database.


Unclassified

AM Technology	Overall Score	Max System Length (ft)	Max System Width (ft)	Max System Height (ft)	System Weight (lbs)
LD002R LCD Resin 3D	97.37410849	0.725	0.725	1.322	15.43
FlashForge Adventurer 3 Lite	64.06893106	1.273	1.115	1.329	28.66
3 Extended	63.95795732	1.12	1.25	1.6	24.91
2 Extended	63.51186064	1.17	1.12	1.6	26.46
FlashForge Creator Max Dual Extruder	61.71196353	1.05	1.532	1.25	32.628
2+	61.51870713	1.12	1.51	1.9	22.7
MarkForged Mark Two	59.64990788	1.92	1.08	1.16	35
Mini 2	57.63945666	1.5	1.11	1.99	26.5
Form 3	52.91090809	1.33	1.23	1.74	38.5
Taz 6	46.09604655	2.69	1.71	1.71	33
Method X-Carbon Fiber Edition	42.34191965	1.4	1.4	2.13	65
Funmat HT Enhanced	33.37374801	1.604	1.75	2.167	165
Replicator Z18	32.90963498	1.85	1.62	2.825	90
F410	30.79724739	2.38	2.54	2.13	85
CR10 Max 3d	27.84943632				54.67
UPrint SE Plus	27.54314732	2.08	2.17	2.58	168
Ultra One	25.61302521	2.5	2.5	2.5	170
Felix Pro XL	23.29070275	2.97	2.19	3.17	176.37
F120	22.55067386	2.85	2.36	2.92	275
Creatbot D600/600 Pro	19.76915464	3	2.77	3.56	275.58
i3 MK3S+	19.76915464				

Figure 32. Initial Analysis Results with Missing Attribute Values

The other aspect to note is that the AM systems missing some attribute values scored particularly low. This is because without attribute values, the score is calculated using a worst case value to help scale the scores without eliminating an attribute entirely. Since these values are easily attainable, and otherwise make the analysis of these two specific AM systems questionable, it was decided to search for these values and manually update the database. Upon doing so, the AM analysis was executed again with the results shown in Figure 33. The i3 MK35+ system from PRUSA, which was missing information during the initial analysis, was originally ranked as the lowest scoring system. Once all the attribute values were included in the analysis, it is now ranked as the second highest system. This highlights that the results of the AMPAT analysis are only as good as the information that is collected and input into the tool.



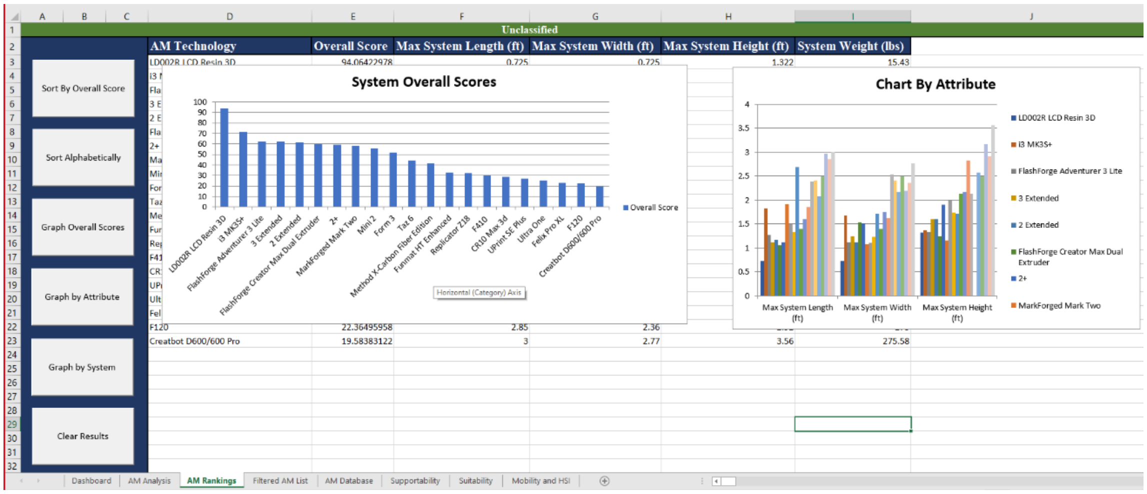
Unclassified

AM Technology	Overall Score	Max System Length (ft)	Max System Width (ft)	Max System Height (ft)	System Weight (lbs)
LD002R LCD Resin 3D	94.06422978	0.725	0.725	1.322	15.43
i3 MK3S+	71.58449208	1.83	1.67	1.375	14
FlashForge Adventurer 3 Lite	62.28695519	1.273	1.115	1.329	28.66
3 Extended	61.90771932	1.12	1.25	1.6	24.91
2 Extended	61.5817235	1.17	1.12	1.6	26.46
FlashForge Creator Max Dual Extruder	60.14669969	1.05	1.532	1.25	32.628
2+	59.26886446	1.12	1.51	1.9	22.7
MarkForged Mark Two	58.19072421	1.92	1.08	1.16	35
Mini 2	55.71223294	1.5	1.11	1.99	26.5
Form 3	51.58437748	1.33	1.23	1.74	38.5
Taz 6	44.54842751	2.69	1.71	1.71	33
Method X-Carbon Fiber Edition	41.55620536	1.4	1.4	2.13	65
Funmat HT Enhanced	33.0642242	1.604	1.75	2.167	165
Replicator Z18	32.34217467	1.85	1.62	2.825	90
CR10 Max 3d	31.82476946	2.41	2.41	2.54	54.67
F410	30.19640705	2.38	2.54	2.13	85
UPrint SE Plus	27.23915072	2.08	2.17	2.58	168
Ultra One	25.31260504	2.5	2.5	2.5	170
Felix Pro XL	23.00113294	2.97	2.19	3.17	176.37
F120	22.36495958	2.85	2.36	2.92	275
Creatbot D600/600 Pro	19.58383122	3	2.77	3.56	275.58

Figure 33. Analysis with All Attribute Values

The AMPAT also provides the user with the ability to view the systems in various plots. These plots provide quick visual representations to help the user better understand the results. Different plot views are shown in Figure 34. After the user examines the results of the analysis, they can decide which systems are worth further investigation. The user can manually remove systems based on their rank scores or due to being completely, or near completely, dominated.

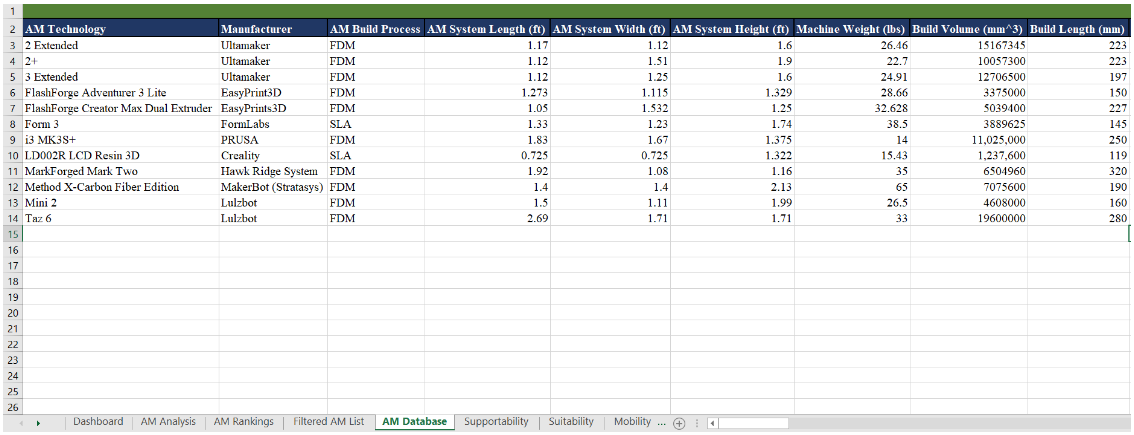
The user can create a new database, composed of only their desired systems. Note that this is not required but can help with future analysis as the sourcing detailed information for systems can consume a lot of effort. However, it is important to note that some systems ranking low in early analysis may comparatively rank higher in further analysis due to new information. Where to draw this line of evaluation is up to the user, their preferences, and expertise. For this scenario, the user decides they are only interested in further examining the systems with an overall score of 55 or higher, as there appears to be a separation of systems at that point.



AM Technology	Overall Score	Max System Length (ft)	Max System Width (ft)	Max System Height (ft)	System Weight (lbs)
LD002R LCD Resin 3D	94.06422978	0.725	0.725	1.322	15.43
F120	22.36495958	2.85	2.36	[illegible]	[illegible]
Creatbot D600/600 Pro	19.58383122	3	2.77	3.56	275.58

Figure 34. Plotted Results from Initial Analysis

Since the decision analysis process is an iterative process and not all the desired attributes and characteristics of AM systems have been evaluated; additional attributes will be identified to conduct further research. With a decreased list of 12 AM systems, shown in Figure 35, the user can strategically decide which attributes to research in more detail. In this scenario, the user can set up additional filters and weight attributes for the following attributes: print dimensions (i.e., length, width, and height), system cost, and consumable cost.

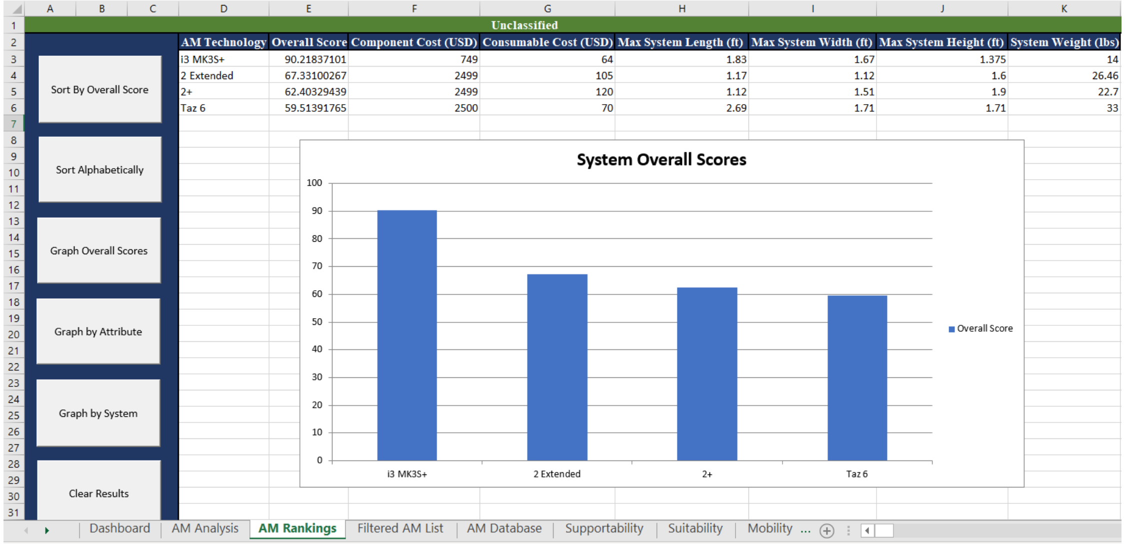


AM Technology	Manufacturer	AM Build Process	AM System Length (ft)	AM System Width (ft)	AM System Height (ft)	Machine Weight (lbs)	Build Volume (mm^3)	Build Length (mm)
2 Extended	Ultamaker	FDM	1.17	1.12	1.6	26.46	15167345	223
2+	Ultamaker	FDM	1.12	1.51	1.9	22.7	10057300	223
3 Extended	Ultamaker	FDM	1.12	1.25	1.6	24.91	12706500	197
FlashForge Adventurer 3 Lite	EasyPrint3D	FDM	1.273	1.115	1.329	28.66	3375000	150
FlashForge Creator Max Dual Extruder	EasyPrints3D	FDM	1.05	1.532	1.25	32.628	5039400	227
Form 3	FormLabs	SLA	1.33	1.23	1.74	38.5	3889625	145
i3 MK3S+	PRUSA	FDM	1.83	1.67	1.375	14	11,025,000	250
LD002R LCD Resin 3D	Creality	SLA	0.725	0.725	1.322	15.43	1,237,600	119
MarkForged Mark Two	Hawk Ridge System	FDM	1.92	1.08	1.16	35	6504960	320
Method X-Carbon Fiber Edition	MakerBot (Stratasys)	FDM	1.4	1.4	2.13	65	7075600	190
Mini 2	Lulzbot	FDM	1.5	1.11	1.99	26.5	4608000	160
Taz 6	Lulzbot	FDM	2.69	1.71	1.71	33	19600000	280

Figure 35. Down-selected AM System Database

The desired print dimensions are based on the types of parts to be fabricated and the method used for fabrication. The minimum print dimension filter is set to 200mm length, 200mm width, and 125mm height. The system (component) cost is the initial procurement cost of the item. The user decides to use the manufacturer's suggested retail price (MSRP) in place of a customized quote based on quantity and lead times. While the system cost has an impact on the decision, it only represents a small portion of the overall system lifecycle cost, and therefore is given a weight of only 40. Conversely, consumable cost is re-occurring and of interest to the user because it can represent long term costs that need to be considered, therefore it is given a weight of 50.

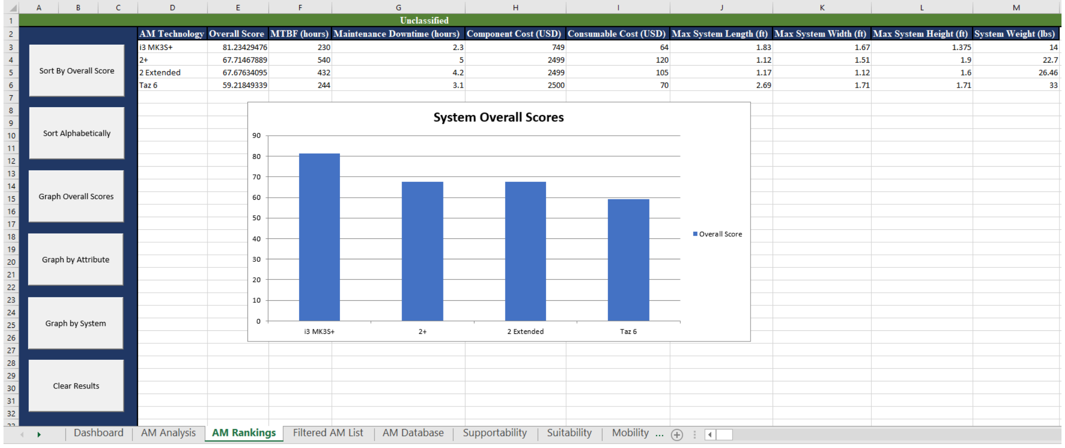
The analysis is executed again with the updated analysis criteria, resulting in a higher number of filtered systems and a new ranking of scores. These new results are shown in Figure 36. Since there now remains only four systems through the filter, and three have relatively similar scores, the user decides to perform a thorough investigation into the reliability of each of these systems to aide in further decision analysis.


Unclassified

AM Technology	Overall Score	Component Cost (USD)	Consumable Cost (USD)	Max System Length (ft)	Max System Width (ft)	Max System Height (ft)	System Weight (lbs)
i3 MK3S+	90.21837101	749	64	1.83	1.67	1.375	14
2 Extended	67.33100267	2499	105	1.17	1.12	1.6	26.46
2+	62.40329439	2499	120	1.12	1.51	1.9	22.7
Taz 6	59.51391765	2500	70	2.69	1.71	1.71	33

Figure 36. Analysis Results with Updated Criteria

The desired attributes from the reliability research are MTBF and MDT. This will inform the user of how often a system fails (MTBF), and how long it will take to get the system running again (MDT). The user decides to perform this analysis on four systems of interest, as shown in Figure 37. The MDT and MTBF are given weights of 80 and 90 respectfully. The user then executes the analysis again, which yields the results shown in Figure 37. The gap between the system scores has decreased, indicating that the systems with a higher cost have a higher reliability. However, the i3 MK3S+ still prevails as the highest ranked system.



Unclassified

AM Technology	Overall Score	MTBF (hours)	Maintenance Downtime (hours)	Component Cost (USD)	Consumable Cost (USD)	Max System Length (ft)	Max System Width (ft)	Max System Height (ft)	System Weight (lbs)
i3 MK3S+	81.23429476	230	2.3	749	64	1.83	1.67	1.375	14
2+	67.71467889	540	5	2499	120	1.12	1.51	1.9	22.7
2 Extended	67.67634095	432	4.2	2499	105	1.17	1.12	1.6	26.46
Taz 6	59.21849339	244	3.1	2500	70	2.69	1.71	1.71	33

Figure 37. Final Analysis Results

Given that the AMPAT is an Excel-based application, it is possible to utilize native Excel capabilities to examine the scores of each of the systems outside of the function buttons in the AMPAT. For example, if the user would like to view the overall score of each system based on their system cost, this can be done by utilizing the scatter plot in Excel, shown in Figure 38 (note that the 2+ and 2 Extended have similar scores, thus overlap in the scatter plot). The results of the scatter plot indicate that the overall performance of the i3 MK3S+ surpasses that of the other systems. These results could be used to inform investment and procurement decisions (e.g., the i3 MK3S+ has a 3:1 cost benefit compared to the other systems).

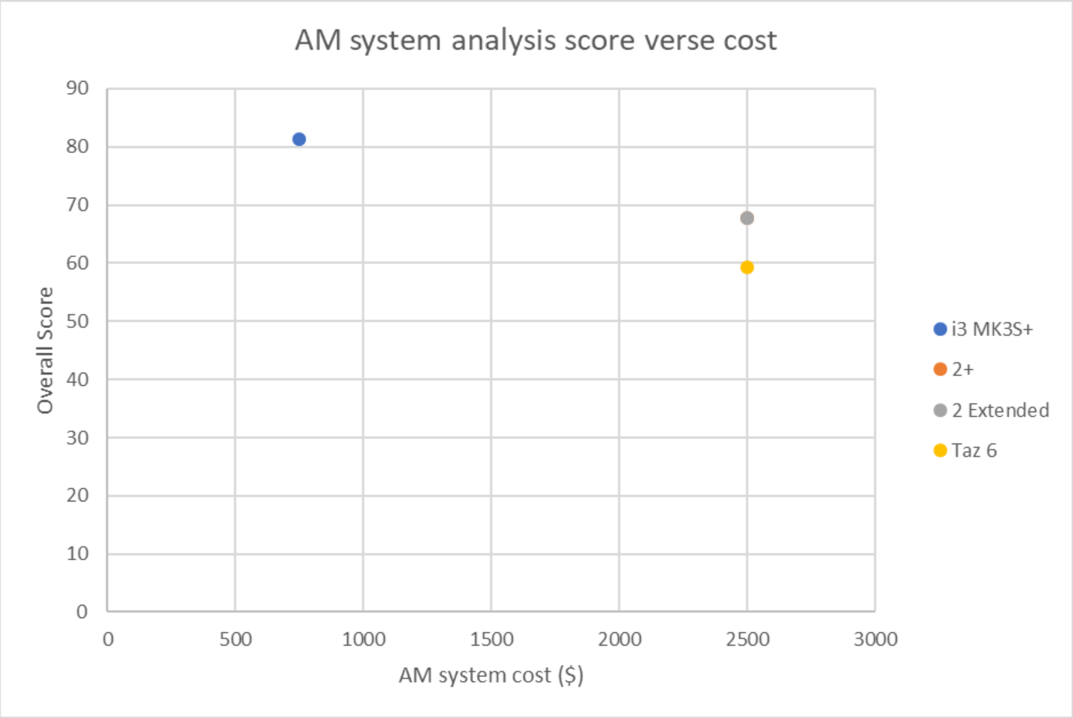


Figure 38. Scatter Plot of AM Systems Overall Score vs. System Initial Cost (note: 2+ and 2 Extended overlap in the scatter plot)

While this analysis provides a clear picture for the decision maker, it also allows the user to continually update the databases with additional systems, or update and add new attributes of existing systems. Users can modify the database as their experience with a system grows or as new capabilities and technologies become available. Further, new attributes of interest can be added to the filtering over time, such as the ability to transport the AM system. A system that was otherwise ranked high may be excluded due to further research into the system and its limitations.

VI. ANALYSIS RESULTS

This chapter provides an overview of the process that the NEAM team used to verify and validate that the AMPAT met stakeholder needs and satisfied the project requirements. Additionally, this chapter re-visits the project research questions and provides conclusions for how the AMPAT deliverable can be used and tailored by stakeholders to address the research questions for specific expeditionary environments.

A. VERIFICATION AND VALIDATION OF AMPAT REQUIREMENTS

This section describes the methodology used to execute the V&V step of the SE process for this project. The requirements verification & validation test matrix (RVTM) shown in Table 3 is provided to show traceability of test cases to specific project requirements. Each test in the RVTM includes a description of the test scenario, the functionality that is intended to be tested, and the requirement(s) that the test satisfies.

A test plan was developed for each of the test scenarios identified in Table 3, including the input parameters for the user to enter and the expected outputs from the AMPAT analysis. After the user ran each test scenario, the outputs were compared to the provided test plan to ensure consistency. The detailed test case set-ups can be found in Appendix A. Note that test case 3 does not have a test set-up since it tests the AMPAT "Clear Results" button. Each of the tests in Table 3 were conducted by members of the NEAM team who were not involved with the coding of the tool. This method ensured that the test scenarios were easy for a standard user to understand and follow, and that the functionality worked as expected.

Table 3. Requirements Verification and Validation Test Matrix (RVTM)

Test #	Test Scenario	Functionality Tested	Requirement(s)	Test Result
1	Select option for filtering of the AM database using mock database information.	Ability to filter based on user-defined selections.	14.a, 14.c	Pass
		Clarity of User Guide instructions.	17, 18, 22.a, 23.a	
2	Assign weights to each attribute using mock database information.	Ability to weigh user-selected attributes.	14.b, 14.c	Pass
		Clarity of User Guide instructions.	15.a, 17, 22.a, 23.a	
3	Clear results and selections using clear button.	Ability to clear all results and selections.	16, 22.a, 23.a	Pass
4	Add AM system using fillable form.	Ability to add AM systems to the database via a user form.	12.b, 12.c	Pass
		Clarity of User Guide instructions.	15.a, 16, 17, 22.a.ii,23.a.ii,	
5	Add AM system manually.	Ability to add AM systems to the database manually.	11, 12.a, 12.b, 12.c	Pass
		Clarity of User Guide instructions.	15.a, 16, 17, 22.a.i,23.a.i,	
6	Modify AM system.	Ability to modify existing AM systems in the database.	11, 12.a, 12.b, 12.c	Pass
		Clarity of User Guide instructions.	15.a, 16, 17, 22.a.i,23.a.i,	
7	Error check database.	Ability to identify errors in the database.	13.a,13.b,13.c	Pass
		Clarity of User Guide instructions.	15.c, 22.a.iii, 23.a.iii	
8	Repeat tests 1 – 2.	Ability to identify additions and modifications to the database.	15.a, 16, 17, 18, 22.a.iv, 23.a.iv	Pass

Table 3 describes the functionality that the NEAM team was able to exercise dynamically via software testing. Software testing involves running the code to try to generate failures and/or observe operational behavior of the code (Sommerville 2004, 256). In some cases, particularly for non-functional requirements, the NEAM team was unable to verify and validate certain requirements by running the AMPAT. The requirements shown in Table 4 were verified and validated using the static process of software inspection. Software inspection entails analyzing the system in to detect faults and anomalies (Sommerville 2004, 256).

Table 4. Requirements Verified and Validated via Inspection

Requirement Category and #	Requirement	Test Result
Top-Level #1	The decision analysis process shall provide a method to aid a user in analyzing AM systems for use in the following expeditionary environments: Littoral Operations in a Contested Environment. Expeditionary Advanced Base Operations. Distributed Maritime Operations.	Pass
Top-Level #2	The decision analysis process shall allow users to input desired data, such as but not limited to the following: Available AM systems. AM system characteristics. User preference on characteristics.	Pass
Top-Level #3	The decision analysis process shall provide an output to assist the user in the decision-making process.	Pass
Database Functionality #4	The analysis tool shall allow for the inclusion of an AM technology database to support expeditionary missions.	Pass
Database Content #5	The AM technology database shall include various AM system specifications for the decision analysis process to analyze and provide an output to the user.	Pass
Database Content #6	The AM technology database shall contain but is not limited to the following AM system information attributes: Build dimensions Build material Build process System dimensions Print speed Cooling requirements Print quality Post processing requirements	Pass
Database Content #7	The values within an attribute shall all be of the same unit of measure.	Pass

Requirement Category and #	**Requirement**	**Test Result**
Database Content #8	The AM technology database shall include a user-modifiable sample of available AM technologies at the time of development with a cut-off date of 31 March 2021 for new data. The sample shall include machines that cover a range of available materials and capabilities. At a minimum the sample will include 40 AM systems with the following characteristics: There shall be a variance in accepted material type (metal, plastic, composites). Printers with varying print precision (in all dimensions, i.e., x, y z) Printers with varying print speeds. Printers with varying filament thicknesses (where appropriate) Printers with varying hot bed temperatures (where appropriate). Printers with varying print qualities (layer thickness). Printers with a variance in print bed area (small is considered less than 5in x 5in, medium is considered between 5inx5in and 8in x 8in, large is considered greater than 8in x 8in). Printers that require post processing of materials and printers that do not require post processing of materials before parts can be used.	Pass
Database Content #9	The database shall include a notes section for each printer to be filled in at the users' discretion with relevant information not captured in other database categories.	Pass
Database Updates #10	The database shall not cap the number of AM technologies that can be added.	Pass
Operating System #19	The decision analysis process shall be developed in software that is available to DON users.	Pass
Operating System #20	The decision analysis process software shall be compatible with Windows and OSX operating systems.	Pass
Operating System #21	The application software hosting the decision analysis process shall allow for future development for users to implement source code modifications if desired.	Pass
System Use #24	The analysis tool and database shall be constructed with open information (unclassified publicly available information), allowing free sharing within the DOD, contractors, and other potential users.	Pass

Inspection and software testing are complementary techniques that should be used together to check conformance with specifications, requirements, and non-functional characteristics (Sommerville 2004, 256). The combination of software testing and inspection techniques allowed the NEAM team to comprehensively verify and validate that the AMPAT was developed correctly and fulfilled the project requirements.

B. ADDRESSING RESEARCH QUESTIONS

This project focused on three primary research questions:

1. What AM equipment would best serve the force in execution of DMO/LOCE/EABO including the consideration of interoperability with other USMC and Navy forces?
2. What are the most advantageous dispersions of AM capabilities across the fleet to maximize benefits including potential prepositioning of equipment?
3. How can NECC better integrate their capabilities into the greater naval mission?

Conclusions for the research questions are summarized as follows:

The first research question can be answered by using the AMPAT to conduct customized, iterative analysis with user-defined inputs that are tailored to a specific expeditionary environment and use case. Figure 39 shows the process that the AMPAT uses to complete the analysis. The first step of the process is to populate the database with potential AM systems. Next, the user must populate the appropriate attribute values for supportability, suitability, and mobility/HSI tabs within the AMPAT. From there, the AM systems are filtered based on mission requirements and then scored based on decision maker preferences. The user will then be presented with results that they can review and use to draw comparisons between systems. This will allow the user to down-select systems and iteratively repeat the analysis process by populating more attribute values for the AM systems, which will produce more detailed analysis results.

Figure 39. AMPAT Analysis Process

For the second research question, the NEAM team was unable to develop a fully informed dispersion plan to address the second research question due to the sensitivity of aggregating information about AM systems that are fielded at specific locations and units throughout the fleet. However, stakeholders can easily up-domain the AMPAT to an environment with the appropriate security classification and customize the analysis for the tool to provide recommendations for AM systems for specific locations in the fleet. Scenario C described in Chapter V, section 3C provides an example of how a user can run AMPAT with their own set of inputs to down-select to a recommended list of AM systems for a specific mission. Given the proper inputs, the results of this analysis could be used to determine the best strategy to preposition AM technologies throughout the fleet.

The third research question requires a comprehensive approach that includes the development of an all-encompassing AM naval strategy document and the use of AMPAT to conduct customized analysis as discussed in the former paragraphs of this section. In order to better integrate AM capabilities into the greater Navy mission, the NECC should collaborate and strategize with the various organizations that work with AM technologies and contribute to the development of DOD AM policy. The NEAM team worked with many of these organizations throughout the course of this project, including: NAVFAC Engineering and Expeditionary Warfare Center, Naval Sea Systems Command Technology

Office, Marine Corps Systems Command, Naval Surface Warfare Center Indian Head Division, Naval Surface Warfare Center Pt. Hueneme Division, 1st Marine Logistics Group, Marine Forces Command, Naval Supply Systems Command (NAVSUP), Naval Information Warfare Center Pacific, and the Office of Naval Research. One of the biggest gaps that the NEAM team identified is the need for a consolidated list of DOD approved AM systems. In order to do this, experts within the AM field from the aforementioned organizations must work together to develop a strategy document that establishes criteria necessary to approve AM systems for DOD use. The AMPAT should be used to assist the group of qualified AM SMEs evaluate different AM technologies to determine suitability for DOD missions and operational scenarios. As the users continue to populate AMPAT with additional AM systems and iteratively conduct analysis with varying parameters, the results and outputs from the tool can be used to justify DOD approval decisions. This approach would unify the DON and the DOD to most effectively and efficiently support the needs of the greater naval mission.

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VII. FUTURE WORK AND CONCLUSIONS

A. FUTURE WORK

As mentioned in Chapter I, section B, additional work is required to refine and expand upon the research and AMPAT deliverable to maximize the benefits to the DON and DOD. The NEAM team identified the following items for consideration of future work.

- Material properties should be added as an attribute to the AMPAT deliverable to allow users to identify the best AM design and support materials to use against degradation or corrosion.

- AM equipment from all branches of the DOD should be added to the AMPAT database to minimize duplication of efforts and maximize return on investment for specific AM systems.

- The AMPAT should be up-domained to a higher security classification environment to allow for use of controlled unclassified (CUI) and/or classified inputs. This would allow for more comprehensive analysis pertaining to specific locations in the fleet to make informed decisions about prepositioning of AM equipment.

- The AMPAT should be used to conduct analysis and recommend AM systems for more advanced maintenance, such as depot-level repair or construction operations. While the scenarios in Chapter 5 focus on using AM systems to build replacements parts, there is also an interest within the DOD to use AM as much as possible for major repairs and overhaul (Coyle 2017).

- In addition to the AM technology database inherent in AMPAT, the tool should be expanded upon to include a library or repository of parts and part specifications. This would expand the utility of AMPAT and allow it to make recommendations for AM systems that should be used to print specific parts to support ships, submarines, aircraft, and other vehicles or equipment.

- The DOD should investigate the integration of the AMPAT with the Additive Manufacturing Cost Analysis Tool (AMCAT), developed and maintained by NAVSUP. AMCAT provides users with a cost analysis for the price of procuring a part vs. the price of printing a part with AM equipment. AMCAT also has potential to aggregate metrics based on collected data, such as usability and reliability attributes. The integration of AMPAT and AMCAT has the potential to provide the DOD with a powerful, all-encompassing tool that can provide technical and cost analysis of AM systems and parts to fulfill specific operational missions.

- A configuration management plan or program should be developed to keep track of the most current version of the AMPAT. As the tool will be delivered to multiple organizations and users, it would be most beneficial to have a process in place to ensure that all modifications and additions are accessible by all stakeholders.

- As the AM field continues to grow at a rapid pace, the DOD should conduct analysis to determine necessary security measures for AM systems, particularly pertaining to cyber threats and the use of foreign AM systems and the potential impacts on the fleet (Sadagic and Brutzman 2017).

- All DOD organizations involved with AM development and implementation should work to develop a unified certification program to identify DOD approved AM equipment. Additionally, the DOD should provide training programs and materials to all users to ensure safety and proper use.

- The DOD should continue efforts to analyze procedures and methods for designing, developing, validating, and integrating new AM equipment and parts. As AM equipment is approved for DOD use, it should be added to the AMPAT for users to expand and refine analysis.

B. CONCLUSIONS

The use of AM is growing rapidly throughout the DON and DOD in an effort to increase readiness and sustainment and enhance warfighting capabilities (Hull 2019; Department of the Navy 2017). Currently, the DOD uses many different user-friendly, low-cost COTS AM printers to expedite the procurement process and decrease the length of training time (Fuentes 2019). As a result of the nonconformity of AM systems across the DOD, inefficiencies are more likely to occur such as redundant training, false assumptions, and increased user errors. This research, along with the AMPAT deliverable, can help align the DON and DOD to progress AM technology in a unified effort to support the needs of the greater naval mission.

The NEAM team used a modified Waterfall Process Model systems engineering approach to execute this project. First, stakeholder needs were captured and the requirements were defined using the mission definition and system objectives. Next, information was gathered on current and prospective AM methods and applications through detailed literature reviews that spanned current AM capabilities, applications of AM within industry, and specific DOD capabilities and limitations. From there, all potential software options that could be used to satisfy the defined requirements were identified and an AoA was conducted to select the best software to satisfy stakeholder needs and requirements. The tool was developed in Excel, using the VBA programming language. The team applied a modified agile software development philosophy by defining the MVP, approaching code development with a modular design, and by identifying additional capabilities and features to implement in the code after the MVP was developed and thoroughly tested. Once the MVP was complete, an RVTM was developed for V&V of the tool and a combination of inspection and testing techniques were used to verify and validate that the AMPAT was developed correctly and met system requirements. Throughout the SE process, the final report and associated deliverables (i.e., user guide, tutorial videos) were developed simultaneously.

As demonstrated in Chapter V, the analysis performed using AMPAT can be applied to a range of scenarios, including large-scale missions aboard amphibious ships to smaller, tailored missions that are constrained to specific attributes. The AMPAT empowers the user to conduct customized, iterative analysis with user-defined inputs that are tailored to a specific use case.

The AMPAT deliverable fulfills the purpose, objectives, and research questions associated with this project by providing the NECC with a tool and decision-making process to recommend specific AM equipment to be used on deployed systems, platforms, and vehicles in various environments including: DMO, LOCE, and EABO. Although this research and development was constrained to the unclassified level, The AMPAT can be used in higher classification environments with inputs that are tailored to specific locations to inform dispersion plans that will provide guidance on how best to preposition AM equipment throughout the fleet. Lastly, analysis ran through the AMPAT can be used to justify DOD approval decisions for AM equipment, which would help the NECC integrate their capabilities into the greater Navy mission.

APPENDIX: TEST CASES

A. TEST CASE 1 SET-UP

Test 1.a		Test 1.b		Test 1.c	
Attribute	**Input**	**Attribute**	**Input**	**Attribute**	**Input**
Enter Min Build Length (mm)	10	Enter Min Build Length (mm)	10	Enter Min Build Length (mm)	100
Enter Min Build Width (mm)	20	Enter Min Build Width (mm)	20	Enter Min Build Width (mm)	180
Enter Min Build Height (mm)	30	Enter Min Build Height (mm)	30	Enter Min Build Height (mm)	150
Build Material	plastic	Build Material	metal	Build Material	metal
Build Process	fdm	Build Process	DED	Build Process	powder bed fusion
Enter System Dimensions Max Length (ft)	30	Enter System Dimensions Max Length (ft)	15	Enter System Dimensions Max Length (ft)	20
Enter System Dimension Max Width (ft)	30	Enter System Dimension Max Width (ft)	15	Enter System Dimension Max Width (ft)	25
Enter System Dimension Max Height (ft)	30	Enter System Dimension Max Height (ft)	15	Enter System Dimension Max Height (ft)	20
Enter Max System Weight (lbs)	300	Enter Max System Weight (lbs)	30000	Enter Max System Weight (lbs)	30000
Enter Min Print Speed (mm/sec)	100	Enter Min Print Speed (mm/sec)	200	Enter Min Print Speed (mm/sec)	
System Cooling Requirements	-	System Cooling Requirements		System Cooling Requirements	
Print Quality (Resolution)	100	Print Quality (Resolution)		Print Quality (Resolution)	
ComponentPost Processing	-	ComponentPost Processing	subtractive	ComponentPost Processing	none
Select Country of Origin	-	Select Country of Origin		Select Country of Origin	
DoD Pre-Approved?	no	DoD Pre-Approved?		DoD Pre-Approved?	no status
Can the System be Moved After Initial Installation?	yes	Can the System be Moved After Initial Installation?		Can the System be Moved After Initial Installation?	
PPE Required?	no	PPE Required?		PPE Required?	
Transportability	-	Transportability		Transportability	
Operable on the Move?	-	Operable on the Move?		Operable on the Move?	
Requires Hazardous Waste Removal?	-	Requires Hazardous Waste Removal?		Requires Hazardous Waste Removal?	

B. TEST CASE 2 SET-UP

Test 2 Filter inputs (Remains the same for Tests 2.a - 2.c)		Test 2.a		Test 2.b		Test 2.c	
Attribute	**Input**	**Attribute**	**Weight**	**Attribute**	**Weight**	**Attribute**	**Weight**
Enter Min Build Length (mm)	100	MTBF	75	MTBF	75	MTBF	75
Enter Min Build Width (mm)	180	MCMT	50	MCMT	50	MCMT	50
Enter Min Build Height (mm)	150	Material Availablilty	30	Material Availablilty	30	Material Availablilty	30
Build Material	metal			personnel training rate	40	personnel training rate	40
Build Process	powder bed fusion			avg operating temp	60	avg operating temp	60
Enter System Dimensions Max Length (ft)	20					mean time between maintenance	60
Enter System Dimension Max Width (ft)	25					operational availability	60
Enter System Dimension Max Height (ft)	20						
Enter Max System Weight (lbs)	30000						
Enter Min Print Speed (mm/sec)							
System Cooling Requirements							
Print Quality (Resolution)							
ComponentPost Processing	none						
Select Country of Origin							
DoD Pre-Approved?	no status						
Can the System be Moved After Initial Installation?							
PPE Required?							
Transportability							
Operable on the Move?							
Requires Hazardous Waste Removal?							

C. TEST CASE 4 SET-UP

4.a		4.b		4.c	
Attribute	**Input**	**Attribute**	**Input**	**Attribute**	**Input**
AM Technology	Avance-42	AM Technology	Rwby	AM Technology	MST3K
Manufacturer	MICE inc.	Manufacturer	Velo 3D	Manufacturer	EOS
AM Build Process	Powder Bed Fusion	AM Build Process	Powder Bed Fusion	AM Build Process	Powder Bed Fusion
AM System Length (ft)	15.41	AM System Length (ft)	6.89	AM System Length (ft)	19.69
AM System Width (ft)	20.28	AM System Width (ft)	6.89	AM System Width (ft)	21.33
AM System Height (ft)	9.84	AM System Height (ft)	8.2	AM System Height (ft)	7.68
Machine Weight (lbs)	24250.85	Machine Weight (lbs)	12560	Machine Weight (lbs)	10218.5
Build Volume (mm^3)	180000000	Build Volume (mm^3)	99225000	Build Volume (mm^3)	
Build Length (mm)	600	Build Length (mm)	315	Build Length (mm)	
Build Width (mm)	600	Build Width (mm)	315	Build Width (mm)	
Build Height (mm)	500	Build Height (mm)	1000	Build Height (mm)	
Power Requirements	43000	Power Requirements		Power Requirements	
Printing Speed		Printing Speed		Printing Speed	
Print Quality		Print Quality		Print Quality	
Filament Size		Filament Size		Filament Size	
Cooling Requirements		Cooling Requirements		Cooling Requirements	
Post Processing Manual Removal of Support Material	FALSE	Post Processing Manual Removal of Support Material	FALSE	Post Processing Manual Removal of Support Material	FALSE
Post Processing Chemical Bath	FALSE	Post Processing Chemical Bath	FALSE	Post Processing Chemical Bath	FALSE
Post Processing Subtractive Machining	FALSE	Post Processing Subtractive Machining	FALSE	Post Processing Subtractive Machining	TRUE
Other Post Processing Method	FALSE	Other Post Processing Method	FALSE	Other Post Processing Method	FALSE
Ceramic Print Material	FALSE	Ceramic Print Material	FALSE	Ceramic Print Material	FALSE
Types of Ceramic Print Material		Types of Ceramic Print Material		Types of Ceramic Print Material	
Plastic Print Material	FALSE	Plastic Print Material	FALSE	Plastic Print Material	FALSE
Types of Plastic Print Material		Types of Plastic Print Material		Types of Plastic Print Material	
Metal Print Material	TRUE	Metal Print Material	TRUE	Metal Print Material	TRUE
Types of Metal Print Material		Types of Metal Print Material		Types of Metal Print Material	Aluminum, Maraging Steel, Nickel Alloy, Titanium
Concrete Print Material	FALSE	Concrete Print Material	FALSE	Concrete Print Material	TRUE
Types of Conrete Print Material		Types of Conrete Print Material		Types of Conrete Print Material	
Cost (USD)		Cost (USD)		Cost (USD)	
Country of Origin		Country of Origin		Country of Origin	Germany
DoD Approved		DoD Approved		DoD Approved	
Movable After Installation		Movable After Installation		Movable After Installation	
PPE Requirement		PPE Requirement		PPE Requirement	
Non-Mobile System		Non-Mobile System		Non-Mobile System	
Movable by Crane		Movable by Crane		Movable by Crane	
Movable by Forklift		Movable by Forklift		Movable by Forklift	
Built in Wheels		Built in Wheels		Built in Wheels	
Movable by One-Man Lift		Movable by One-Man Lift		Movable by One-Man Lift	
Movable by Two-Man Lift		Movable by Two-Man Lift		Movable by Two-Man Lift	
Operable on the Move		Operable on the Move		Operable on the Move	
Requires Hazardous Waste Removal		Requires Hazardous Waste Removal		Requires Hazardous Waste Removal	

4.a		4.b		4.c	
Attribute	**Input**	**Attribute**	**Input**	**Attribute**	**Input**
Failure Rate (hours)	23	Failure Rate (hours)	17	Failure Rate (hours)	
MTBF (hours)	23	MTBF (hours)	60	MTBF (hours)	
Mean Corrective Maintenance Time (hours)	63	Mean Corrective Maintenance Time (hours)	50	Mean Corrective Maintenance Time (hours)	
Mean Preventative Maintenance Time (hours)	46	Mean Preventative Maintenance Time (hours)	36	Mean Preventative Maintenance Time (hours)	
Mean Active Corrective Maintenance Time (hours)	43	Mean Active Corrective Maintenance Time (hours)	13	Mean Active Corrective Maintenance Time (hours)	
Mean Active Maintenance Time (hours)	36	Mean Active Maintenance Time (hours)	27	Mean Active Maintenance Time (hours)	
Maximum Active Corrective Maintenance Time (hours)	24	Maximum Active Corrective Maintenance Time (hours)	32	Maximum Active Corrective Maintenance Time (hours)	
Logistics Delay Time (hours)	16	Logistics Delay Time (hours)	60	Logistics Delay Time (hours)	
Administrative Delay Time (hours)	57	Administrative Delay Time (hours)	62	Administrative Delay Time (hours)	
Maintenance Downtime (hours)	36	Maintenance Downtime (hours)	53	Maintenance Downtime (hours)	
Mean Time Between Maintenance (hours)	54	Mean Time Between Maintenance (hours)	68	Mean Time Between Maintenance (hours)	
Mean Time Between Replacement (hours)	21	Mean Time Between Replacement (hours)	17	Mean Time Between Replacement (hours)	
Inherent Availability	12	Inherent Availability	56	Inherent Availability	
Achieved Availability	50	Achieved Availability	35	Achieved Availability	
Operational Availability	27	Operational Availability	67	Operational Availability	
Spares/Repair Parts Demand Rate	38	Spares/Repair Parts Demand Rate	55	Spares/Repair Parts Demand Rate	
Spares/Repair Part Processing Time (hours)	15	Spares/Repair Part Processing Time (hours)	27	Spares/Repair Part Processing Time (hours)	
Probability of Spares Availability	12	Probability of Spares Availability	59	Probability of Spares Availability	
Probability of Success with Spares	47	Probability of Success with Spares	31	Probability of Success with Spares	
Material Availability	24	Material Availability		Material Availability	56
Software Availability	59	Software Availability		Software Availability	49
Time Necessary for Post Processing (hours)	17	Time Necessary for Post Processing (hours)		Time Necessary for Post Processing (hours)	71
Availability of Troubleshooting/Help	51	Availability of Troubleshooting/Help		Availability of Troubleshooting/Help	78
Initial Spares and Inventory Cost (USD)	77	Initial Spares and Inventory Cost (USD)		Initial Spares and Inventory Cost (USD)	72
Personnel Training Cost (USD)	32	Personnel Training Cost (USD)		Personnel Training Cost (USD)	37
Distribution and Transportation Cost (USD)	23	Distribution and Transportation Cost (USD)		Distribution and Transportation Cost (USD)	54
Unscheduled Maintenance Cost (USD)	78	Unscheduled Maintenance Cost (USD)		Unscheduled Maintenance Cost (USD)	12
Component Cost (USD)	62	Component Cost (USD)		Component Cost (USD)	69
Material Cost per lb (USD)	27	Material Cost per lb (USD)		Material Cost per lb (USD)	52
Consumable Cost per 100hrs Operation (USD)	22	Consumable Cost per 100hrs Operation (USD)		Consumable Cost per 100hrs Operation (USD)	52
Max Vibration Endurance (Hz)	24	Max Vibration Endurance (Hz)	54	Max Vibration Endurance (Hz)	
Average Operating Temperature (Celsius)	59	Average Operating Temperature (Celsius)	44	Average Operating Temperature (Celsius)	
Max Operating Temperature (Celsius)	17	Max Operating Temperature (Celsius)	28	Max Operating Temperature (Celsius)	
Min Operating Temperature (Celsius)	51	Min Operating Temperature (Celsius)	15	Min Operating Temperature (Celsius)	
Maximum Operating Humidity (%)	77	Maximum Operating Humidity (%)	67	Maximum Operating Humidity (%)	
Manpower Necessary to Operate (Number of persons)	32	Manpower Necessary to Operate (Number of persons)	40	Manpower Necessary to Operate (Number of persons)	
Operator Labor Hours per Hour of System Operation	23	Operator Labor Hours per Hour of System Operation	44	Operator Labor Hours per Hour of System Operation	
Personnel Training Rate (personnel trained/hour)	78	Personnel Training Rate (personnel trained/hour)	21	Personnel Training Rate (personnel trained/hour)	
Max System Length (ft)	15.41	Max System Length (ft)	6.89	Max System Length (ft)	
Max System Width (ft)	20.28	Max System Width (ft)	6.89	Max System Width (ft)	
Max System Height (ft)	9.84	Max System Height (ft)	8.2	Max System Height (ft)	
System Weight (lbs)	24250.85	System Weight (lbs)	12560	System Weight (lbs)	
Average Thermal Output (BTU)	54	Average Thermal Output (BTU)	28	Average Thermal Output (BTU)	
Maximum Thermal Output (BTU)	62	Maximum Thermal Output (BTU)	12	Maximum Thermal Output (BTU)	

D. TEST CASE 5 SET-UP

5.a		5.b		5.c	
Attribute	**Input**	**Attribute**	**Input**	**Attribute**	**Input**
AM Technology	Avance-84	AM Technology	Emerald	AM Technology	M400
Manufacturer	AM enterprises	Manufacturer		Manufacturer	EOS
AM Build Process	Powder Bed Fusion	AM Build Process	Powder Bed Fusion	AM Build Process	Powder Bed Fusion
AM System Length (ft)	15.41	AM System Length (ft)	6.89	AM System Length (ft)	19.69
AM System Width (ft)	20.28	AM System Width (ft)	6.89	AM System Width (ft)	21.33
AM System Height (ft)	9.84	AM System Height (ft)	8.2	AM System Height (ft)	7.68
Machine Weight (lbs)	24250.85	Machine Weight (lbs)	12560	Machine Weight (lbs)	10218.5
Build Volume (mm^3)	180000000	Build Volume (mm^3)	99225000	Build Volume (mm^3)	64,000,000
Build Length (mm)	600	Build Length (mm)	315	Build Length (mm)	400
Build Width (mm)	600	Build Width (mm)	315	Build Width (mm)	400
Build Height (mm)	500	Build Height (mm)	1000	Build Height (mm)	400
Power Requirements	43000	Power Requirements		Power Requirements	16220
Printing Speed		Printing Speed		Printing Speed	7000
Print Quality		Print Quality		Print Quality	90
Filament Size		Filament Size		Filament Size	
Cooling Requirements		Cooling Requirements		Cooling Requirements	
Post Processing Manual Removal of Support Material	FALSE	Post Processing Manual Removal of Support Material	FALSE	Post Processing Manual Removal of Support Material	FALSE
Post Processing Chemical Bath	FALSE	Post Processing Chemical Bath	FALSE	Post Processing Chemical Bath	FALSE
Post Processing Subtractive Machining	FALSE	Post Processing Subtractive Machining	FALSE	Post Processing Subtractive Machining	TRUE
Other Post Processing Method	FALSE	Other Post Processing Method	FALSE	Other Post Processing Method	FALSE
Ceramic Print Material	FALSE	Ceramic Print Material	FALSE	Ceramic Print Material	FALSE
Types of Ceramic Print Material		Types of Ceramic Print Material		Types of Ceramic Print Material	
Plastic Print Material	FALSE	Plastic Print Material	FALSE	Plastic Print Material	FALSE
Types of Plastic Print Material		Types of Plastic Print Material		Types of Plastic Print Material	
Metal Print Material	TRUE	Metal Print Material	TRUE	Metal Print Material	TRUE
Types of Metal Print Material		Types of Metal Print Material		Types of Metal Print Material	Aluminum, Maraging Steel, Nickel Alloy, Titanium
Concrete Print Material	FALSE	Concrete Print Material	FALSE	Concrete Print Material	TRUE
Types of Conrete Print Material		Types of Conrete Print Material		Types of Conrete Print Material	
Cost (USD)		Cost (USD)		Cost (USD)	
Country of Origin		Country of Origin		Country of Origin	Germany
DoD Approved		DoD Approved		DoD Approved	
Movable After Installation		Movable After Installation		Movable After Installation	
PPE Requirement		PPE Requirement		PPE Requirement	
Non-Mobile System		Non-Mobile System		Non-Mobile System	
Movable by Crane		Movable by Crane		Movable by Crane	
Movable by Forklift		Movable by Forklift		Movable by Forklift	
Built in Wheels		Built in Wheels		Built in Wheels	
Movable by One-Man Lift		Movable by One-Man Lift		Movable by One-Man Lift	
Movable by Two-Man Lift		Movable by Two-Man Lift		Movable by Two-Man Lift	
Operable on the Move		Operable on the Move		Operable on the Move	
Requires Hazardous Waste Removal		Requires Hazardous Waste Removal		Requires Hazardous Waste Removal	

5.a		5.b		5.c	
Attribute	**Input**	**Attribute**	**Input**	**Attribute**	**Input**
Failure Rate (hours)	23	Failure Rate (hours)	17	Failure Rate (hours)	
MTBF (hours)	23	MTBF (hours)	60	MTBF (hours)	
Mean Corrective Maintenance Time (hours)	63	Mean Corrective Maintenance Time (hours)	50	Mean Corrective Maintenance Time (hours)	
Mean Preventative Maintenance Time (hours)	46	Mean Preventative Maintenance Time (hours)	36	Mean Preventative Maintenance Time (hours)	
Mean Active Corrective Maintenance Time (hours)	43	Mean Active Corrective Maintenance Time (hours)	13	Mean Active Corrective Maintenance Time (hours)	
Mean Active Maintenance Time (hours)	36	Mean Active Maintenance Time (hours)	27	Mean Active Maintenance Time (hours)	
Maximum Active Corrective Maintenance Time (hours)	24	Maximum Active Corrective Maintenance Time (hours)	32	Maximum Active Corrective Maintenance Time (hours)	
Logistics Delay Time (hours)	16	Logistics Delay Time (hours)	60	Logistics Delay Time (hours)	
Administrative Delay Time (hours)	57	Administrative Delay Time (hours)	62	Administrative Delay Time (hours)	
Maintenance Downtime (hours)	36	Maintenance Downtime (hours)	53	Maintenance Downtime (hours)	
Mean Time Between Maintenance (hours)	54	Mean Time Between Maintenance (hours)	68	Mean Time Between Maintenance (hours)	
Mean Time Between Replacement (hours)	21	Mean Time Between Replacement (hours)	17	Mean Time Between Replacement (hours)	
Inherent Availability	12	Inherent Availability	56	Inherent Availability	
Achieved Availability	50	Achieved Availability	35	Achieved Availability	
Operational Availability	27	Operational Availability	67	Operational Availability	
Spares/Repair Parts Demand Rate	38	Spares/Repair Parts Demand Rate	55	Spares/Repair Parts Demand Rate	
Spares/Repair Part Processing Time (hours)	15	Spares/Repair Part Processing Time (hours)	27	Spares/Repair Part Processing Time (hours)	
Probability of Spares Availability	12	Probability of Spares Availability	59	Probability of Spares Availability	
Probability of Success with Spares	47	Probability of Success with Spares	31	Probability of Success with Spares	
Material Availability	24	Material Availability	54	Material Availability	56
Software Availability	59	Software Availability	44	Software Availability	49
Time Necessary for Post Processing (hours)	17	Time Necessary for Post Processing (hours)	28	Time Necessary for Post Processing (hours)	71
Availability of Troubleshooting/Help	51	Availability of Troubleshooting/Help	15	Availability of Troubleshooting/Help	78
Initial Spares and Inventory Cost (USD)	77	Initial Spares and Inventory Cost (USD)	67	Initial Spares and Inventory Cost (USD)	72
Personnel Training Cost (USD)	32	Personnel Training Cost (USD)	40	Personnel Training Cost (USD)	37
Distribution and Transportation Cost (USD)	23	Distribution and Transportation Cost (USD)	44	Distribution and Transportation Cost (USD)	54
Unscheduled Maintenance Cost (USD)	78	Unscheduled Maintenance Cost (USD)	21	Unscheduled Maintenance Cost (USD)	12
Component Cost (USD)	62	Component Cost (USD)	19	Component Cost (USD)	69
Material Cost per lb (USD)	27	Material Cost per lb (USD)	13	Material Cost per lb (USD)	52
Consumable Cost per 100hrs Operation (USD)	22	Consumable Cost per 100hrs Operation (USD)	20	Consumable Cost per 100hrs Operation (USD)	52
Max Vibration Endurance (Hz)	24	Max Vibration Endurance (Hz)	54	Max Vibration Endurance (Hz)	
Average Operating Temperature (Celsius)	59	Average Operating Temperature (Celsius)	44	Average Operating Temperature (Celsius)	
Max Operating Temperature (Celsius)	17	Max Operating Temperature (Celsius)	28	Max Operating Temperature (Celsius)	
Min Operating Temperature (Celsius)	51	Min Operating Temperature (Celsius)	15	Min Operating Temperature (Celsius)	
Maximum Operating Humidity (%)	77	Maximum Operating Humidity (%)	67	Maximum Operating Humidity (%)	
Manpower Necessary to Operate (Number of persons)	32	Manpower Necessary to Operate (Number of persons)	40	Manpower Necessary to Operate (Number of persons)	
Operator Labor Hours per Hour of System Operation	23	Operator Labor Hours per Hour of System Operation	44	Operator Labor Hours per Hour of System Operation	
Personnel Training Rate (personnel trained/hour)	78	Personnel Training Rate (personnel trained/hour)	21	Personnel Training Rate (personnel trained/hour)	
Max System Length (ft)	15.41	Max System Length (ft)	6.89	Max System Length (ft)	
Max System Width (ft)	20.28	Max System Width (ft)	6.89	Max System Width (ft)	
Max System Height (ft)	9.84	Max System Height (ft)	8.2	Max System Height (ft)	
System Weight (lbs)	24250.85	System Weight (lbs)	12560	System Weight (lbs)	
Average Thermal Output (BTU)	54	Average Thermal Output (BTU)	28	Average Thermal Output (BTU)	
Maximum Thermal Output (BTU)	62	Maximum Thermal Output (BTU)	12	Maximum Thermal Output (BTU)	

E. TEST CASE 6 SET-UP

6		
Attribute	**Current Entry**	**New Entry**
AM Technology	Emerald	
Manufacturer		
AM Build Process	Powder Bed Fusion	
AM System Length (ft)	6.89	
AM System Width (ft)	6.89	ten
AM System Height (ft)	8.2	
Machine Weight (lbs)	12560	
Build Volume (mm^3)	99225000	
Build Length (mm)	315	
Build Width (mm)	315	
Build Height (mm)	1000	
Power Requirements		
Printing Speed		
Print Quality		
Filament Size		
Cooling Requirements		
Post Processing Manual Removal of Support Material	FALSE	TRUE
Post Processing Chemical Bath	FALSE	
Post Processing Subtractive Machining	FALSE	
Other Post Processing Method	FALSE	
Ceramic Print Material	FALSE	
Types of Ceramic Print Material		
Plastic Print Material	FALSE	
Types of Plastic Print Material		
Metal Print Material	TRUE	
Types of Metal Print Material		
Concrete Print Material	FALSE	
Types of Conrete Print Material		

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6		
Attribute	**Current Entry**	**New Entry**
Cost (USD)		
Country of Origin		
DoD Approved		
Movable After Installation		
PPE Requirement		
Non-Mobile System		
Movable by Crane		
Movable by Forklift		
Built in Wheels		
Movable by One-Man Lift		
Movable by Two-Man Lift		
Operable on the Move		
Requires Hazardous Waste Removal		
Failure Rate (hours)	17	
MTBF (hours)	60	75
Mean Corrective Maintenance Time (hours)	50	
Mean Preventative Maintenance Time (hours)	36	
Mean Active Corrective Maintenance Time (hours)	13	
Mean Active Maintenance Time (hours)	27	
Maximum Active Corrective Maintenance Time (hours)	32	
Logistics Delay Time (hours)	60	
Administrative Delay Time (hours)	62	
Maintenance Downtime (hours)	53	
Mean Time Between Maintenance (hours)	68	
Mean Time Between Replacement (hours)	17	
Inherent Availability	56	
Achieved Availability	35	
Operational Availability	67	

6		
Attribute	**Current Entry**	**New Entry**
Spares/Repair Parts Demand Rate	55	65
Spares/Repair Part Processing Time (hours)	27	
Probability of Spares Availability	59	
Probability of Success with Spares	31	
Material Availability		
Software Availability		
Time Necessary for Post Processing (hours)		
Availability of Troubleshooting/Help		
Initial Spares and Inventory Cost (USD)		
Personnel Training Cost (USD)		
Distribution and Transportation Cost (USD)		
Unscheduled Maintenance Cost (USD)		
Component Cost (USD)		
Material Cost per lb (USD)		
Consumable Cost per 100hrs Operation (USD)		
Max Vibration Endurance (Hz)	54	
Average Operating Temperature (Celsius)	44	
Max Operating Temperature (Celsius)	28	
Min Operating Temperature (Celsius)	15	
Maximum Operating Humidity (%)	67	
Manpower Necessary to Operate (Number of persons)	40	
Operator Labor Hours per Hour of System Operation	44	
Personnel Training Rate (personnel trained/hour)	21	
Max System Length (ft)	6.89	
Max System Width (ft)	6.89	
Max System Height (ft)	8.2	
System Weight (lbs)	12560	
Average Thermal Output (BTU)	28	
Maximum Thermal Output (BTU)	12	

F. TEST CASE 7 ERRORS AND CORRECTIONS

Error / Warning	Correction	
Duplicate system Error	Delete one of the M400 system duplicates	
Incorrect AM system data Error	Correct the Emerald AM system width from ten to 10	
Missing Supplemental AM System Data Warning	Complete the system data with the following information:	
	AM System	RWBY
	Material Availability	54
	Software Availability	44
	Time Necessary for Post Processing (hours)	28
	Availability of Troubleshooting/Help	15
	Initial Spares and Inventory Cost (USD)	67
	Personnel Training Cost (USD)	40
	Distribution and Transportation Cost (USD)	44
	Unscheduled Maintenance Cost (USD)	21
	Component Cost (USD)	19
	Material Cost per lb (USD)	13
Missing Required AM system data Error	Complete the system data with the following information:	
	Consumable Cost per 100hrs Operation (USD)	20
	AM system	MST3K
	Build Volume (mm^3)	64,000,000
	Build Length (mm)	400
	Build Width (mm)	400
	Build Height (mm)	400
	Power Requirements	16220
	Printing Speed	7000
	Print Quality	90

G. TEST CASE 8 SET-UP

Test 8.a			Test 8.b			Test 8.c		
Attribute	**Input**	**Weight**	**Attribute**	**Input**	**Weight**	**Attribute**	**Input**	**Weight**
Enter Min Build Length (mm)	100		Enter Min Build Length (mm)	100		Enter Min Build Length (mm)	100	
Enter Min Build Width (mm)	180		Enter Min Build Width (mm)	180		Enter Min Build Width (mm)	180	
Enter Min Build Height (mm)	150		Enter Min Build Height (mm)	150		Enter Min Build Height (mm)	150	
Build Material	metal		Build Material	metal		Build Material	metal	
Build Process	powder bed fusion		Build Process	powder bed fusion		Build Process	powder bed fusion	
Enter System Dimensions Max Length (ft)	20		Enter System Dimensions Max Length (ft)	20		Enter System Dimensions Max Length (ft)	20	
Enter System Dimension Max	25		Enter System Dimension Max	25		Enter System Dimension Max	25	
Enter System Dimension Max	20		Enter System Dimension Max	20		Enter System Dimension Max	20	
Enter Max System Weight	30000		Enter Max System Weight	30000		Enter Max System Weight (lbs)	30000	
MTBF		75	MTBF		75	MTBF		75
MCMT		50	MCMT		50	MCMT		50
Material Availablilty		30	Material Availablilty		30	Material Availablilty		30
			personnel training rate		40	personnel training rate		40
			avg operating temp		60	avg operating temp		60
						mean time between maintenance		60
						operational availability		60

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