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Operationalizing Metal Additive Manufacturing for Expeditionary Employment by the United States Marine Corps

March 2023

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Naval Postgraduate School

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ABSTRACT

This thesis examines four metal additive manufacturing (AM) processes and assesses their suitability for ground expeditionary operations by the United States Marine Corps (USMC) through a cost effectiveness analysis. Metal AM, while in use in industrial applications for many years, has reached a maturity level where expeditionary employment is viable. However, a knowledge gap exists in understanding which technology is best suited for deployed operations. Concurrent with metal AM technology advancements, the USMC is conducting a significant reorganization and refocus on supporting distributed naval operations against peer threats, requiring new sustainment concepts. This thesis examines the cost effectiveness of each AM process to enable a reduced logistics footprint through production of parts as far forward and close to the point of need as possible, limiting supply stockpile size and minimizing transportation costs. Using AM process characteristics, printer cost data, and total quantity of parts produced over a five-year period, the cost-effectiveness (CE) ratio determined for each candidate process supports the recommendation of a hybrid AM process as the most cost-effective alternative.

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LIST OF ACRONYMS AND ABBREVIATIONS

3DP	three-dimensional printing/printer
ABS	acrylonitrile butadiene styrene
ADT	administrative downtime
AM	additive manufacturing
BMD	bound metal deposition
CAD	computer-aided design
CBA	cost benefit analysis
CEA	cost effective(ness) analysis
CLB	Combat Logistics Battalion
CONUS	continental United States
CPG	Commandant’s Planning Guidance
CNC	computer numerical control
DED	directed energy deposition
DO	distributed operations
DOD	Department of Defense
DON	Department of the Navy
EAB	expeditionary advanced base
EABO	expeditionary advanced base/basing operations
FDM	fused deposition modeling
FFF	fused filament fabrication
LCT	Littoral Combat Team
LDT	logistics downtime
LLB	Littoral Logistics Battalion
MAM	metal additive manufacturing
MARADMIN	Marine administrative message
MCO	Marine Corps order
MDT	mean downtime

MEF	Marine Expeditionary Force
MIM	metal injection molding
MLR	Marine Littoral Regiment
MOS	military occupational specialty
NPS	Naval Postgraduate School
OCONUS	outside the continental United States
OEM	original equipment manufacturer
SEMS	Shop Equipment, Maintenance Shop
SM	subtractive manufacturing
TACFAB	Tactical Fabrication System United
USMC	States Marine Corps
WAAM	wire arc additive manufacturing
XFAB	Expeditionary Fabrication Facility

EXECUTIVE SUMMARY

This thesis examines four metal additive manufacturing (AM) processes and assesses their suitability for ground expeditionary operations by the United States Marine Corps (USMC) through a cost effectiveness analysis. Concurrent with metal AM technology advancements, the USMC is conducting a significant reorganization and refocus on supporting distributed naval operations against peer threats, requiring new sustainment concepts. By examining current technologies and operational concepts, this thesis presents a decision-making framework which supports the selection of a metal AM process for adoption and integration into USMC expeditionary operations.

The Marine Corps began experimenting with additive manufacturing (AM) in 2016 with the release of Marine administrative message (MARADMIN) 489/16 and released definitive intent to adopt AM with the publication of Marine Corps Order (MCO) 4700.4, *Additive Manufacturing Policy* in March 2020 (Headquarters Marine Corps [HQMC], 2016; HQMC, 2020). MCO 4700.4 provided the official framework for AM employment in the Marine Corps. In 2019, the Marine Corps embarked on a significant transformation, undertaking changes to talent management and force composition, organization and structure, and weapon mix and employment concepts (Commandant of the Marine Corps [CMC], 2019). Underpinning these changes is a return to naval and expeditionary employment of Marine forces in an operational environment characterized by distributed forces competing against peer or near-peer competitors (CMC, 2019). The Marine Corps requires new sustainment concepts to enable and support this operational vision (USMC, 2021). Concurrent with the Marine Corps' experimentation and force redesign efforts are significant developments in metal AM technology. Metal AM, while in use in industrial methods for many years now, is reaching a maturity level where expeditionary employment is viable and provides a new sustainment capability to support the modern operating environment. This thesis focuses on metal AM and its suitability for ground maintenance in expeditionary operations by the United States Marine Corps.

Several processes exist for additive manufacturing with metal; however, many of these processes have requirements that make them unsuitable for expeditionary operations,

including highly controlled print environments, hazardous or sensitive raw material (e.g., powdered metals), or large equipment lacking the transportability needed for deployment via military assets. Factoring these constraints, four processes with characteristics suitable for expeditionary employment were selected for analysis: hybrid AM (specifically wire-arc AM, or WAAM), liquid metal, fused filament fabrication (FFF), and bound metal deposition (BMD).

A cost effectiveness analysis (CEA) was used to estimate and assess the operational benefits that each process could provide. A CEA is an appropriate analysis for programs where the benefits are hard to place a monetary value on (Cellini & Kee, 2010). In the case of expeditionary metal AM, the derived benefits are difficult to estimate and monetize, as the desired program outcome is sustainment of a deployed force (thereby enabling mission effectiveness and mission accomplishment). Complicating the assessment of operational benefits are the actions occurring before the print process and after the final part is produced: the supply system must supply raw print material, while maintainer personnel must install the AM-produced parts. The AM process itself cannot control these two steps, so intuitive program outcomes in terms of the operational availability or readiness of deployed force are problematic for assessing a metal AM process's cost effectiveness.

Thus, to quantify the benefit obtained from metal AM, total quantity of parts produced over a five-year system operational lifetime was selected as a proxy. A five-year operational lifetime represents an optimal timespan in which the Marine Corps can effectively adopt and integrate metal AM into operations and then reassess the specific metal AM equipment adopted to take advantage of technological advancements over the five years.

To determine the cost effectiveness of each process, a single representative manufacturer and model was chosen for each of the four processes: 3D Hybrid Solutions (hybrid AM, WAAM), Xerox ElemX (liquid metal), Markforged Metal X (FFF), and Desktop Metal Studio System 2 (BMD). System costs and representative print times were determined using open-source data available from the manufacturers and industry websites. The representative print times allowed for the estimation of the total number of parts produced in a five-year period. Dividing the total system cost by the total number of parts produced resulted in a cost effectiveness ratio for each process, in terms of cost (dollars) per part produced.

Through examination of operational concepts, metal AM process attributes, and the conduct of a cost-effectiveness analysis, the hybrid AM process was found to the be preferred method for expeditionary employment by the Marine Corps. Hybrid AM offers a superior cost-effectiveness ratio in terms of cost per part over a five-year operational lifetime, along with a more versatile process which can be readily adapted to mission requirements.

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I. INTRODUCTION

This chapter describes the purpose, research questions, scope, and structure of this thesis. Additionally, the specific contribution of this research is discussed. The research questions are addressed using a cost effectiveness analysis, which factors system cost and total parts produced over a five-year system operational lifetime. Those two parameters enable the determination of a cost effectiveness ratio each of the four metal AM processes examined, with hybrid additive manufacturing achieving the superior cost effectiveness ratio.

A. PURPOSE

Additive manufacturing (AM) is a rapidly developing technology with recognized potential as a disruptive force in many industries, including military applications. AM is a broad term that encompasses many different process variations and materials. This thesis focuses on metal AM and its suitability for expeditionary operations by the United States Marine Corps (USMC). The USMC began fielding the Expeditionary Fabrication (XFAB) facility in June 2022, which contains a suite of polymer additive manufacturing capabilities and support peripherals. This system does not currently have a metal AM capability but is scheduled to receive the capability in Fiscal Year 2025, with the exact system and process type still to be determined. Operational experimentation has been conducted since 2018 with a hybrid AM system as part of the Expeditionary Manufacturing (ExMan) system. Processes under consideration by the Marine Corps for official adoption as part of the XFAB facility include wire arc additive manufacturing (WAAM) in a hybrid process, fused filament fabrication (FFF)/fused deposition modeling (FDM), liquid metal, and bound metal deposition (BMD).

Metal AM, while in use in industrial methods for many years now, is reaching a maturity level where expeditionary employment is viable. Much research has been done on the utility of AM for military applications, ranging from depot-level manufacture of out-of-production parts to cost-benefit analyses of individual printers. However, the capability to use metal AM outside of an established laboratory or industrial facility is a relatively new development, leaving a gap in understanding of metal AM in an expeditionary environment. Additionally, each technology has unique strengths and weaknesses that may make one process better suited for expeditionary employment than another.

A refocus by the Marine Corps on distributed operations in support of naval campaigns coincides with the technological developments in AM that make expeditionary employment feasible. The reworked operating concepts call for new operational tactics, techniques, and procedures, along with new technologies to best enable and support them. In this context of reimaging operational concepts and logistics support, metal AM offers a potential transformative technology to enable the reimaged operational concepts. Determining which method offers the most cost-effective solution is crucial for the Marine Corps to begin benefitting from the cutting-edge of metal AM development.

B. RESEARCH QUESTIONS

Primary: What candidate metal AM process offers the most cost-effective alternative?

Findings: Through examination of operational concepts, metal AM processes, and the conduct of a cost-effectiveness analysis, the hybrid AM process was found to offer a superior cost-effectiveness ratio in terms of cost per part over a five-year operational lifetime, along with a more versatile process which can be readily adapted to mission requirements.

Secondary: What are important attributes of a metal 3D printer for use in expeditionary environments by the USMC?

Findings: Through examination of literature, two critical attributes were identified. Feedstock properties (e.g., availability and stability) and durability/deployability of AM machines were identified as attributes that have a significantly influential effect on process performance, effectiveness, and suitability. The importance of print speed on the effectiveness of an AM system was also revealed through the conduct of a cost effectiveness analysis.

C. SCOPE

The context for analysis of expeditionary metal AM for the USMC is in support of ground equipment maintenance in a deployed, austere environment, as this use is less developed than aviation applications and stands to benefit significantly from streamlined logistics and reduced demand levels. Metal AM processes included in the analysis show potential for inclusion in the XFAB system by fitting within the constraints inherent in the system (physical dimensions, weight, etc.).

A cost-effectiveness analysis (CEA) is conducted on four candidate processes of WAAM, liquid metal, FFF/FDM, and BDM. Each of these processes is represented by a single system suite from a single manufacturer: WAAM is represented by the 3D Hybrid Solutions system found in the ExMan; liquid metal is represented by the Xerox ElemX liquid metal printer; FFF/FDM is represented by the Markforged Metal X; and BDM is represented by the Desktop Metal Inc., Studio System 2. Data for each of these systems was accessed via open-source information either available from the manufacturer or industry/trade publications. While other manufacturers may provide similar products using the same basic processes, these were chosen simply to narrow the range of alternatives. In choosing these systems, no specific cost constraints were applied, though cost is a factor in the cost-effectiveness analysis. A specific cost threshold was not included so as not to constrain the range of choices.

To complete the work in this thesis, elements from systems engineering and defense management disciplines were synthesized to produce a cohesive understanding of the metal AM system and determine a preferred AM system. This is achieved through the interdisciplinary examination of the operational context surrounding a metal AM system and the costs, benefits, and trade-offs associated with the selection of a particular system. The use case of ground equipment maintenance in an expeditionary environment provides the front-end analysis required to understand required and desirable system attributes. The cost-effectiveness analysis allows for incorporation of cost elements while addressing and mitigating the difficulty in quantifying benefits in military-specific, tactical scenarios. The influence of operational context-driven requirements combined with the ever-present factor of system cost produces a top-down, integrated analysis of a complete system.

D. SPECIFIC CONTRIBUTION

The main contribution of this thesis is the determination of a preferred metal AM process for expeditionary use by the USMC. This analysis examines metal AM in the context of new USMC operational concepts, force redesign, and modernization efforts. Though the benefits of expeditionary AM have been well established, research focusing exclusively on the use of metal in expeditionary environments is limited. This thesis advances the collective understanding by examining the unique considerations required for expeditionary metal AM and assessing the cost-effectiveness of several candidate metal AM processes. The cost-effectiveness analysis process focused on tangible operational outputs that contribute to the mission effectiveness of a deployed force. The cost-effectiveness process can be updated as refined input parameters become available.

E. REPORT STRUCTURE

This chapter introduced the purpose of the thesis, the research questions, and described the scope of the thesis. Chapter II contains background information including Marine Corps operational concepts and the relevance of metal AM, Marine Corps policy supporting adoption of AM, and current Marine Corps AM equipment and metal technologies under consideration. Chapter III discusses literature relevant to AM in an expeditionary context. Chapter IV discusses the methodology used to conduct the assessment. Chapter V details the conduct of the assessment. Chapter VI discusses the results of the analysis and recommends areas for future research.

II. BACKGROUND

Beginning in 2019 with the release of the 38th Commandant's Planning Guidance, the Marine Corps embarked on a significant transformation, undertaking changes to talent management and force composition, organization and structure, and weapon mix and employment concepts (Commandant of the Marine Corps [CMC], 2019). Underpinning these changes is, broadly speaking, a return to naval and expeditionary employment of Marine forces, away from the established infrastructure and stable logistics networks seen in the forward operating bases in Iraq and Afghanistan. The new operational environment is focused on peer or near-peer competitors in highly contested operations where mobility and presence are expected to be routinely challenged or denied (CMC, 2019). The commandant and the USMC's integrated planning teams have envisioned a future conflict where survivability through minimization of tactical signature is crucial, and lethality through precision-strike while minimizing firing unit exposure is an essential corollary to survivability (CMC, 2019).

Necessary to creating a low-signature force is a reduction in the logistical tail of deployed forces as this tail often produces a large signature, is difficult to conceal, and can reveal the position of tactical forces through numerous signatures, including administrative and physical. Further complicating the logistical problem is that, in the envisioned operating concept, tactical forces are to be employed in a highly distributed manner, with potentially hundreds of nautical miles separating forward forces from logistical support bases (CMC, 2019). The once championed concept of sea basing and reliance on supporting ashore forces with floating supply centers has been made obsolete with the prevalence of adversary long-range, precision strike capabilities (CMC, 2020).

Thus, reducing the signature of tactical forces to improve survivability comes with a requirement that the logistics forces also contribute to the signature reduction (through any means, either directly or indirectly). If a tactical combat force could be made more self-sufficient and require minimal contact with logistics elements, then those forces would be able to minimize their signature to a greater extent than a similar force that still required regular contact with supporting logistics. This self-sufficiency can be achieved through several mechanisms, varying from the simple (e.g., contingency contracting) to technologically complex (autonomous underwater resupply).

One means being explored by the Marine Corps through which units can be more self-sufficient is through AM. Through AM, a unit can manufacture parts on-demand based on need, drawing from a pool of common feedstock, rather than stocking premanufactured parts with only a single specific application or use. With AM, the physical footprint of logistic forces can be reduced, shrinking the stockpile of repair and replacement parts. Additionally, the logistics reaction time, or lead time, can be shortened as repair parts can be produced in-theater, at or near the point of need, rather than requisitioned from hundreds or thousands of miles away (potentially reaching all the way back to the continental United States).

Various types of AM have been viable technologies for nearly 40 years, but with continued advancements in computing technology, AM technology is finally beginning to leave the heavy industrial base and enter consumer-level use and applications. With the move downward to the consumer level comes the opportunity for expeditionary employment, as advancing technologies require less stringently controlled operating conditions and offer increases in usability. The ability to print objects in metal (as opposed to the more common and easier-to-print polymers) is also increasing the operational relevance of AM, as metal constructed components are well-suited to expeditionary military operations for their strength and durability properties.

This chapter provides an overview of how metal AM can contribute to the success current and near-future Marine Corps operating concepts, reviews the AM systems currently in use by the Marine Corps, and briefly discusses the various metal AM processes under consideration for adoption.

A. MARINE CORPS OPERATING CONCEPTS

The following sections examine current and near-future operational concepts for the Marine Corps. The significance of some of the changes, such as those in the 38th Commandant's Planning Guidance, cannot be overstated. The Marine Corps is undergoing a dramatic reshaping which will influence the characteristics of the service for several decades. The capstone vision for the Marine Corps, referred to as *Force Design: 2030*, contains several justifications for change, with implications affecting the service at the strategic, operational, and tactical levels. Because of the vast amount of guidance and information available in these documents, it is impractical to holistically examine every aspect of every document in this thesis. Describing the operational context in which the metal AM machines will operate is important, as it ensures the requirements placed on a system are justified, reasonable, and rational. As AM is treated as a logistics and sustainment capability, the following sections will focus specifically on logistics and sustainment guidance or implications and assess how AM contributes to the execution of the operating concepts described.

1. 38th Commandant's Planning Guidance

Released in July 2019, the 38th Commandant's Planning Guidance (CPG) sought to refocus the Marine Corps into its primary role of an amphibious force that existed to support the conduct of naval operations—a significant organizational and cultural shift from twenty years of inland counterterrorism and stability operations. Additionally, adversaries of the future are posited to bring advanced capabilities and increased lethality to the battlefield, primarily through detection and precision strike weapons, creating an operating environment in which the Marine Corps is not accustomed to operating (CMC, 2019). The commandant clearly stated his concern: "the greatly extended range, quantity, and accuracy of these observed fires impose new vulnerabilities on the joint force…and necessitate significant changes to the concepts and capabilities by which Marines will conduct expeditionary operations in the immediate future" (CMC, 2019, p. 9). Of primary relevance to a discussion concerning AM is the need to avoid detection and target through the minimization of a force's signature.

The commandant introduces the term "stand-in forces" in his initial guidance, noting that stand-in forces are "designed to generate technically disruptive, tactical stand-in engagements that confront aggressor naval forces with an array of low signature, affordable, and risk-worthy platforms and payloads" (CMC, 2019, p. 10). Stand-in forces would require support from a separate, equally low-signature entity called expeditionary advanced bases (EABs). “Expeditionary Advanced Base Operations (EABO), as an operational concept, enables the naval force to persist forward within the arc of adversary long-range precision fires… EABO are designed to restore force resiliency and enable the persistent naval forward presence” (CMC, 2019, p. 11). This persistence requires an accessible source of supply of repair and maintenance parts for equipment, and the adversary precision strike capability places these supply lines at increased risk, possibly all the way back to the point of embarkation (CMC, 2019).

Closely tied to the idea of EABO and signature reduction is the concept of distributed operations (DO). DO are deemed to be a complementary and necessary piece of EABO, as distribution of forces offers a variety of advantages against the future threat. Five reasons are cited for DO, with the implication common to all is that friendly forces will be spread out over some appreciable distance. This distribution stretches logistic lines across potentially significant distances and necessitates either long supply lines that could expose friendly locations, or the placement of logistic capability forward with each distributed force. This option will reduce the supply line signature and provide each force with its own measure of self-sufficiency. In this context, AM is a prime enabling capability, as it could allow forward forces to manufacture repair parts for degraded or inoperable equipment without requiring a physical connection back to larger, more robust logistical support networks.

Of additional significance for AM is the commandant’s acknowledgement that “Marines aboard L-Class ships as part of an ARG or ESG will remain the benchmark for our forward operating crisis response forces” (CMC, 2019, p. 3). While also addressing the relevance of forward-deployed forces and CONUS-based deployable units, this affirmation of the importance of ship-based Marine forces provides an important basis for further assumptions about resource access for Marines in expeditionary environments. The “benchmark” of ship-based Marine units provides a known support infrastructure of L-Class ships as well as an indisputable operational scenario from which to conduct analysis of AM performance in expeditionary environments.

2. Force Design 2030

Stated by the commandant in his 2019 *Planning Guidance* as his top priority, force design is an intentionally broad term that encompasses all aspects related to modernizing the Marine Corps to meet the updated operational mandates (CMC, 2019). The first publication of a *Force Design* document occurred in March 2020 and contained actionable items and specific guidance to influence the process and update the numerous stakeholders on modernization progress (CMC, 2020). To date, two subsequent, yearly updates have been released in April 2021 and May 2022.

In the initial March 2020 document, *Force Design 2030,* the commandant discussed the concept of force resilience, noting that while attrition is unavoidable in conflict, a force must be able to continue operations despite taking losses (CMC, 2020). In this context, AM can increase the resilience of a force, offering reduced lead time for repair parts and enabling Marines to creatively manufacture "limp home" parts that may require non-factory-specification parts in order to compensate for incurred battle damage. However, the amount of impact that metal AM is able to achieve on force resilience is highly dependent on the nature of damage sustained or part failures, and also on the capacity and capability of the AM machines available.

While some specific weapons systems were mentioned, most of the guidance regarding logistics and operational principles remained broad. In his guidance to modernization design planners as they developed the future naval expeditionary force, the commandant encouraged considerations of new capabilities which he described as "enablers for doing things differently" (CMC, 2020, p. 11). Focus was directed on capabilities required to develop a "truly DO-capable force that can mass effects while minimizing signature; maximize efficient tactical mobility; reduce logistics demand; and expand the range of mutual support across all tactical echelons" (CMC, 2020, p. 12). While metal AM will not produce a DO-capable force alone, it neatly fits the commandant's guidance of a new capability that enables doing things differently, while also contributing to the ability of a force to conduct DO. If AM is employed correctly, it has the potential to allow freedom of maneuver by placing a new level of logistics support (manufacturing) closer to using forces than previously possible at a relatively small scale.

a. Annual Update 1, April 2021

Published a year after the initial *Force Design 2030* guidance, the first annual update offered further insight into logistic requirements to support the new operating concepts and force modernization. Relevant to the adoption of metal AM is the clarification of capabilities required by the modernized force, and that the Marine Corps should not compromise its all-round utility in an effort to support the stand-in force concept. To this end, the commandant directed that logistics capabilities "must be organized to enable and sustain the stand-in force while retaining appropriate capacities to support global crises and contingencies. The mechanisms we employ to sustain stand-in forces must remain applicable for competition crisis and conflict" (CMC, 2021, p. 6). The implication of this guidance is that any AM capability adopted must have the ability to scale up and down throughout the continuum of low-end crisis response to full-on conflict.

Additionally, the annual update contained guidance that, in order to accomplish stand-in force objectives, the Marine Corps would require "resilient sustainment capabilities" that do not rely on outside or external support (CMC, 2021, p. 6). These sustainment capabilities do not necessarily need to be owned by the Marine Corps but can be provided by the naval or joint force (CMC, 2021). This guidance allows for a broadened range of metal AM support options, specifically ship-based support, which can provide more controlled operating environments and potentially greater manufacturing capabilities and capacities.

b. Annual Update 2, May 2022

The most recent guidance available reinforces the importance of resilient logistics networks and new capabilities to enable revised operating concepts. Supporting the feasibility of AM as an important source of supply is the expressed desire for stand-in forces that are "relatively simple to maintain and sustain" (CMC, 2021, p.2). Aiming for simplicity in maintenance and sustainment increases the impact that metal AM may be able to provide. If the Marine Corps was moving towards increased complexity and complicated maintenance requirements, the threshold for AM to clear to be a relevant method of support would be much greater.

The update also specified several areas of force design that require further analysis. Within the category of Concepts and Wargaming, the commandant stated that “the Service must develop concepts for resilient logistics webs in a contested environment with multiple options for support, to include distribution networks, and multi-domain delivery methods” (CMC, 2021, p. 6). Among other contributing components, metal AM forms an important link in a resilient logistics web by distributing a source of supply of repair/maintenance parts away from identifiable and targetable consolidated supply storage facilities.

3. Stand-In Forces

Released in December 2021, *A Concept for Stand-in Forces* expands upon the initial concept introduced in the *38th Commandant’s Planning Guidance*. Stand-in Forces (SIF) are described as small but lethal forces with relatively low maintenance and sustainment requirements that can operate across the entire continuum of conflict (United States Marine Corps [USMC], 2021). SIF are forward-deployed elements that retain a permanent and continual “foothold” across the world, so that they may deter aggressive actions or, in the event of aggression, can facilitate the introduction of more substantial follow-on forces (USMC 2021). The simplicity of maintenance and sustainment of SIF is an important element for the utility of expeditionary metal AM – parts for simple, easy-to-maintain equipment sets are more feasible to be produced in the field than highly complicated, intricate, or sensitive parts requiring precise manufacturing conditions. The document primarily describes, in broad terms, the purpose and utility of SIF and intentionally does not seek to precisely define required capabilities, force size, or other prescriptive specifications.

Sustainment is discussed only briefly (barely one page out of twenty-three total), but topics raised are very complex matters that require careful consideration and lengthy planning. Because the SIF concept relies on maintaining a low profile and minimal signature, achieving logistic sustainability means that SIF should avoid placing logistically intensive systems inside a contested area (USMC, 2021). For the forces inside the contested area, “Marines should think in terms of planning two or more ways to obtain each required element of support to overcome the lethality of the mature precision-strike regime”

(USMC, 2021). The “two or more ways” provides redundancy, which is always a valued trait in logistics planning, but redundancy in some areas of supply is much more difficult to realistically achieve (e.g., Class VIII blood products or non-generic Class IX repair parts). Often these classes of supply can only come through military or U.S. government sources. Redundancy regarding delivery method at the tactical level is marginally more achievable (e.g., via air transport or ground transport), but the more difficult challenge is experienced by moving “up” the supply chain and attempting to find redundant sources of supply. Additive manufacturing can simultaneously help solve both of these redundancy problems: first, AM removes a large portion of the transportation problem by producing items much closer to the point of need; secondly, AM in itself can be viewed as a source of supply for end-use items. However, the source of supply problem is not entirely eliminated as a source of supply for the unformed printer feedstock now becomes the supply problem to solve.

Eight areas of sustainment requiring new approaches or capabilities for stand-in forces in a contested area are discussed. AM has a limited or indirect effect on three of the items: prepositioned stocks and equipment; local contracting to mitigate distribution needs; and short duration, localized defeat of adversary collection. While AM does have a presence in two of these three items (excluding defeat of collections), the impact of AM is indirect and incidental to the concepts themselves. The prepositioning and local contracting items have an inverse relationship to AM, where those concepts support AM rather than AM supporting the concept. AM has a direct influence on the remaining five items, which are discussed here.

- Enhancing supply distribution: The use of automation and data science to predict repair parts needed is discussed; AM could directly use this information to begin manufacturing parts before they are needed, thus achieving an ideal “just in time” logistics scenario where a part in use begins to fail just as an AM machine is finishing producing the replacement part.
- Demand reduction: AM can contribute to reduction of demand from a strategic and operational view, but not necessarily at the tactical level. A reduction of demand would be seen at higher levels as lower demand for

specific repair parts, but the “true” (i.e., specific item) demand would be seen at the operational and tactical levels that manufacture the required items. Higher planning levels (strategic level and the strategic/operational transition points) would see a new demand for generic feedstock. This demand for feedstock would obscure the nature of the true demand (i.e., the specific parts that are actually being demanded). A mechanism to capture what AM printers are manufacturing in the aggregate would be crucial so that repeat equipment part failures could still be identified and addressed at the OEM.

- Resilient installations: AM machines could potentially be consolidated at advanced naval bases to provide a forward-manufacturing base outside of the contested area, but still closer than continental United States (CONUS)-based sources.
- Proximity to point of need: Here, AM is specifically mentioned as a tool to accomplish “composing or assembling capabilities” and “reducing information and material flows” (USMC, 2021, p.22). As discussed in the supply distribution context, a reduction of material flows not entirely accurate, as raw, unformed feedstock would still be a required material flow. However, feedstock offers transportation benefits over manufactured parts (e.g., less vulnerability to damage in transit and more efficient use of cubic transportation space).
- Small vessels: Experimental logistics support vessels have been made via polymer AM by the University of Maine as a proof-of-concept (Lundquist, 2022). One vessel can carry two 20-foot shipping containers, while another can transport a rifle squad and three days sustainment (Lundquist, 2022). As AM technology advances, these vessels could be produced in-theater, offering numerous, expendable distribution platforms.

A Concept for Stand-in Forces is useful in that it describes what broader activities AM will need to support, but the document's focus is, rightfully, on describing the conduct of stand-in forces rather than explicitly detailing how to support them.

4. Tentative Manual for Expeditionary Advanced Base Operations

Published in February 2021, the *Tentative Manual for Expeditionary Advanced Base Operations* (TMEABO) was the initial step in codifying and standardizing the concepts and vocabulary associated with EABO. The document is intended to provide a shared understanding of the nascent concepts that make up EABO; this common baseline can then inform force design experimentation and facilitate development of new support concepts and updated tactics, techniques, and procedures (Headquarters Marine Corps [HQMC], 2021). Specific information regarding logistics and sustainment is found in a dedicated chapter, which offers some additional insight into requirements that influence metal AM selection and employment principles.

The opening sections of Chapter 7, "Sustainment and Littoral Maneuver," note that "littoral forces rely on resilient and agile logistics that adapt to changing environments and conditions to conduct EABO" (HQMC, 2021, p. 7-1). Resilient and agile logistics is directly enabled by AM and this point is highlighted in several areas of the sustainment chapter. The Marine Corps' seven Principles of Logistics—responsiveness, simplicity, flexibility, economy, attainability, sustainability, and survivability—are discussed in the context of EABO. Of these, metal AM most directly contributes to responsiveness and flexibility, although it could be argued that it supports any of the seven principles. Responsiveness in an EABO context is deemed particularly important as the environment demands, among other things, "limiting unnecessary movement, reducing forward-located stockpiles, and reducing signature" (HQMC, 2021, p. 7-1). The discussion of flexibility in an EAB context notes the inherent distributed nature of operations which necessitates the establishment of a "flexible, adaptive distribution network" (HQMC, 2021, p. 7-1). Employing metal AM technology in any future operating environment, to include EAB, will generate the desired attributes noted in the examples given. AM can produce parts at the point of need, ensuring a near-immediate response time; to achieve this same response time with traditional support systems, parts would need to be stockpiled far forward, close to using forces, thereby violating the reduction of signature and forward-located stockpiles. Flexibility can be enhanced by augmenting certain maneuver units with metal AM capability, which can increase their self-sufficiency and provide options to a commander for when and how to logistically sustain units, rather than being forced into a scenario where minimal options exist due to depletion of resources or lack of essential repair parts for a mission-critical system.

Continuing the sustainment analysis is a discussion of the six functions of logistics—supply, maintenance, transportation, general engineering, health services, and services—with AM specifically addressed several times in the maintenance section. The opening sentence sets the tone for the criticality of the maintenance support: "The littoral forces' ability to persist requires positioning of required maintenance capabilities as close to the point of need as feasible" and notes that evacuating inoperative equipment back to rear maintenance areas "reduces the responsiveness of the maintenance system and risks reducing littoral force capacity" (HQMC, 2021, p. 7-1).

Because of the distributed nature of operations, maintenance forces will likely be highly distributed as well. For distributed maintenance forces to be successful, it is noted that they must be complemented by an efficient and responsive supply chain to ensure timely access to needed repair parts, and that AM is one method of improving these aspects (HQMC, 2021). Identifying suitable areas to conduct maintenance is also important, as maintenance sites should ideally "mask the nature of the operations and allow for maintenance support…as far forward as practical to maintain critical items" (HQMC, 2021, p. 7-5). Metal AM is well-suited to this task, as multiple "miniature factories" could be positioned within a Goldilocks distance from supported forces by being close enough to provide responsive support to critical items but being far enough back so as not to give away a friendly position.

The maintenance function discussion concludes with four keys tasks for a littoral force:

- Reporting on material readiness status
- Employment of low-density, high-demand MOSs

- Prepositioning of repair parts
- Employment of additive and subtractive manufacturing capability (HQMC, 2021, p. 7-5)

Excepting the first item, the remaining three directly relate to AM and, in the case of the final item, specifically *is* AM. Metal AM in particular will require a low-density, high-demand MOS to operate effectively and the employment of metal AM will influence the prepositioning of repair parts. While only the maintenance function was specifically discussed in this section, AM's relevance to logistical sustainment and suitability for EABO is woven throughout the *Tentative Manual*.

B. USMC ADDITIVE MANUFACTURING POLICY

The United States Marine Corps made the first steps towards adoption of AM technology in September 2016 with the release of Marine Administrative Message (MARADMIN) number 489/16, *Interim Policy on the Use of Additive Manufacturing (3D Printing) in the Marine Corps*, and subsequently established consistent steps toward adoption through the release of four later MARADMINs; this progress culminated in March 2020 with the release of *Marine Corps Order 4700.4, Additive Manufacturing Policy.* A thorough analysis of these documents was conducted in June 2021 by Vincent Norako in his report, *Analysis on How the Marine Corps has Created Policy and Integrated Additive Manufacturing Throughout the Force.* To repeat a full synopsis and analysis in this paper would be duplicative, but a brief overview focusing on the Marine Corps' interactions with metal AM is provided for context. Additionally, the Marine Corps' newest operational concepts provide a much clearer imperative for AM in expeditionary environments and must be examined to sufficiently understand the constraints and requirements that will be levied on new AM acquisitions for the USMC.

1. MARADMIN 489/16

MARADMIN 489/16 provides a brief discussion of the basics of AM technology, generalized reasoning for USMC interest in AM ("innovative solutions, improved responsiveness, reduced acquisition and life-cycle cost, and ultimately improved readiness"), and acknowledges challenges ("safety, warranties, and intellectual property issues") (HQMC, 2016, para. 2.C). Tellingly, the MARADMIN notes that, "Currently, the maturity of an AM solution to produce an item is highly dependent upon the specific design, process, and material used to produce that item, as well as the intended use of the item" (para 2.C). This caveat still holds true today and has now likely crossed the threshold from period-specific constraint into a timeliness truism, as current AM technology still grapples with this reality. No specific mention of material type was made but it is safe to imply that the only printers that would be purchased would be polymer-based as they are much cheaper, easier to operate and own, and are more widely available.

Additionally, MARADMIN 489/16 established "a Marine Corps-wide call to action for the initial exploration of AM applications, materials, machines, training, standards, and policies" with the stated intent to "allow Marines to explore AM with an informed awareness, mitigation of risks, and required oversight" (para. 3.A). This document provided the framework and guidance for the initial steps towards adoption of AM in the Marine Corps and did so in an intentionally decentralized manner, encouraging Marines to simply experiment and explore the technology to begin the process of organizational learning. Urgency was communicated and instilled in operational unit through the abrupt commencement authorization with no gradual implementation period: "Commands are authorized to immediately begin use of AM technologies to produce, fabricate, or manufacture repair parts" (para 3.B.) within certain procedural maintenance guidelines. Authorized parts for printing were consumables "like hose assemblies, tubing, name plates, decals, and wires" (para. 3.B.) and parts that have such limited needs or applications that no significant production or demand is anticipated (para. 3.B). Some limited coordinating details and instructions were provided, mainly regarding safety and waiver guidelines for parts used in a system of record managed by a program manager and the requirement for units "currently employing AM…to document and submit the specific details of AM machines, materials, processes, 3D design software and print files, and the products produced to date to the cataloging authority" at the Marine Corps' "Next Generation Logistics" initiative (para. 3.G). While machine data was a crucial step to managing AM experimentation and exploration, units had unrestricted freedom to acquire any printer available for legal government purchase. This granted latitude to "cast the net wide" and accelerated organizational learning and experience by maximizing exposure to AM. However, the loose coordination also resulted in inefficiencies and duplicative efforts in some cases, as noted in previous research from 2019: “five years ago, the Marine Corps did not own a single 3D printer—now no single organization in the Corps can track how many printers are scattered throughout the fleet” (Carter, p. 1).

2. MARADMIN 594/17

MARADMIN 594/17 was released on 25 October 2017 by the Deputy Commandant for Installations and Logistics, on behalf of HQMC and applied only to ground equipment, with aviation-specific information contained in a separate message (para. 3.a.2.c) (the aviation-specific message, MARADMIN 209/18, is not covered here due to the focus on ground equipment). Ian Carter’s 2019 master’s thesis, *A Systems Approach to Additive Manufacturing in the Marine Corps,* provides a good summary of MARADMIN 594/17, stating that it:

> updated the guidance on the management and employment of AM technology in the Corps. The largest and most important change was the sorting of parts into notional bins- Red, Yellow, and Green (RYG)- in the supply system. Green items were approved for AM production without prior approval, yellow items could be AM produced with O-5 or higher commander determination and consultation with the appropriate MCSC [Marine Corps Systems Command] point of contact, and red items could be AM produced only in, essentially, dire straits or with significant prior approval at very high levels. (p. 9)

Among other details, MARADMIN 594/17 specified that the green bin was to be “polymer-based (i.e., plastic) items whose form, fit, and function characteristics require no analysis of performance impacts prior to use” (HQMC, 2017, para. 3.a.1.b.2) and made allowances for proof of concepts or prototypes intended to evaluate fit, form, and function characteristics of printed parts. Parts required to be made from metal could then theoretically be manufactured through traditional methods at intermediate-level maintenance units (i.e., Maintenance Battalions) using these prototypes as models. No specific mention of metal AM was made, either through intentional but unstated acknowledgment that no metal AM printer was feasible for purchase, or through simple omission/oversight. The establishment of the red/yellow/green bin framework was a significant procedural and policy step forward for the adoption of AM in the Marine Corps.

3. MARADMIN 055/19

Released approximately 18 months after MARADMIN 594/17, MARADMIN 055/19 recounts the significant advances the institution had made in the three years since the release of the initial exploration authorization in 2016. The advances covered were the status of AM in the Marine Corps, establishment of AM oversight agencies, an improved information exchange portal, and an implementation plan of action and milestones (HQMC, 2019). The progress outlined in this MARADMIN solidified the future of AM within the Marine Corps. Rather than dictating new or updated policy, the MARADMIN instead highlights the progress made since 2016, noting that the Marine Corps had: deployed over 160 3D printers; added 200 new individual parts to the information exchange portal; deployed metal printers aboard Marine Corps Logistic Bases Albany and Barstow and all three Marine Expeditionary Forces; and deployed an expeditionary capability in a coalition environment (HQMC, 2019). The appearance of metal printers and deployment of an expeditionary capability are the markers of progress most significant to this research, as this is the first documentation of both the relevant environment (deployed/expeditionary) and specific capability (metal).

Moving this combination even one step further, MARADMIN 055/19 documents the deployment of "the first metal 3D printer in support of SPMAGTF-CR Kuwait [Special Purpose Marine Air Ground Task Force—Crisis Response Kuwait]" (HQMC, 2019, para. 2.d). This printer is a hybrid variety, featuring a combination of AM and subtractive manufacturing (CNC machining); this technology and its application will be explored in depth in a later chapter. Related to specific systems, MARADMIN 055/19 also introduces the first two formal programs of record, the Expeditionary Fabrication system (XFAB) and the Tactical Fabrication system (TACFAB). These two systems will also be discussed later in this thesis. And finally, MARADMIN 055/19 details the establishment of the Additive Manufacturing Operating Cell (AMOC) at MCSC. This organization provides the locus of

AM oversight and management in the Marine Corps and provides the knowledge base required to implement AM fully and effectively at scale in the Corps.

4. MCO 4700.4

The cancellation of MARADMINs 489/16, 594/17, and 055/19 on 14 May 2020 in parallel with the announcement of the capstone AM document, *Marine Corps Order 4700.4, Additive Manufacturing Policy* was a major forward advance in permanent adoption of AM in the USMC; service-wide concurrence and release of this order was the final step needed to formalize AM's long-term presence in the Marine Corps. Prior to an official Marine Corps Order, the only formal guidance available was contained in MARADAMINs and, as explained in the preceding sections, this guidance was intentionally loose to encourage the "experimentation phase."

While significant gains were made in gaining familiarity with AM technology, a downside was that without standardized equipment, the actual AM capability across the force was at best inconsistent, or at worst completely unknown. This problem manifests beyond the individual using units to the institutional level, with a knowledge gap of what capability exists within the force, what problems it can reliably solve, or what a "technological goal" for official adoption, acquisition, and integration should look like. Published by Headquarters Marine Corps (HQMC) in March 2020, *Marine Corps Order (MCO) 4700.4, Additive Manufacturing Policy,* acknowledges the need to improve the process of adoption by expressing the commander's intent as: "Improve and standardize implementation of AM at all levels of command across the Marine Corps enterprise in both garrison and deployed environments" (p. 1). An extensive and thorough analysis of MCO 4700.4 was conducted by Norako in a master's thesis, *Analysis on how the Marine Corps has Created Policy and Integrated Additive Manufacturing Throughout the Force* (2021), where he concluded that "overall, the Marine Corps has effectively integrated AM technology within the force and predominantly through the publication of MCO 4700.4" (p. 67). While the majority of the order focuses on establishing the procedural framework for controlled implementation of AM, including equipment accountability, parts approval process, legal considerations, and training, the document does specify that the commander's desired end state for AM is "to leverage AM to the maximum extent to reduce maintenance cycle times, supply chain backlogs, and place manufacturing capabilities at or near the point of need" (p. 1).

Operational employment goals, visions, or objectives are discussed in a limited manner, mainly to provide context for the rest of the order. The order places a significant amount of confidence in the capabilities of AM, at times bordering on hyperbolic bravado: "In a strategic environment where the Marine Corps must fight and win against near-peer competitors in hostile environments, AM creates the opportunity to fully realize the value of distributed operations" and close operational capability gaps such as equipment obsolescence, long lead times for replacement parts, defunct parts suppliers, or countering emerging threats (HQMC, 2020, p. 1-1). These high expectations are worth examining, either to validate that they are feasible and facilitate their existence, or to manage expectations and prevent over-investment.

A broad, conceptual employment model is also provided, offering a baseline framework for AM operations without being overly prescriptive. Four levels of employment are described, paralleling the levels of maintenance (organizational, intermediate, depot) while adding "installation" (HQMC, 2020). As this thesis focuses on operational, expeditionary employment context, the installation description is omitted. A summary of the levels is provided in Table 1.

Table 1. Summary of AM Levels of Operations. Adapted from HQMC (2020).

Level	Description
Organizational	Basic print capability via TACFAB
	Limited design capability: primary source of part designs is from an approved, central repository
	Rapid prototyping for emergent operational necessities
Intermediate	XFAB is the primary AM tool
Depot	The most capable metal and polymer AM systems
	Able to print all types of specialized materials (i.e., metal alloys, polymers, and exotics)

MCO 4700.4 was never intended to offer detailed descriptions of operational employment methods or concepts, but rather to build a framework from which AM could be deliberately adopted by the Marine Corps and integrated into all levels of the force. The contexts provide make the development of operational employment models possible through the delineation of levels of AM operations and the desired capability at each level.

C. USMC FABRICATION SYSTEM DESCRIPTIONS

1. Shop, Equipment, Machine Shop

The Shops, Equipment, Machine Shops (SEMS) is a containerized mobile machine shop which forms the core set of capabilities for conducting intermediate-level maintenance in a field/expeditionary environment. According to Monique Randolph of Marine Corps System Command (MCSC) Office of Public Affairs and Communication, the SEMS is a "deployable shelter equipped with a milling machine, lathe, and other tools to quickly repair damaged vehicle parts, weapons, and other equipment" (Randolph, 2017, para. 5). These traditional, subtractive manufacturing methods are the standard set of capabilities for intermediate-level maintenance, and the XFAB would serve as an additional, complementary capability (Randolph, 2017). Because any metal AM capability adopted would be considered supplementary to the SEMS, it is unlikely that a metal AM capability would be deployed independently of the SEMS. Thus, the fabrication capabilities resident in the SEMS become an important component to include when considering which metal AM system to adopt.

2. Tactical Fabrication System

The Tactical Fabrication (TACFAB) is the system to be employed by all USMC units for a polymer-only AM capability at the organizational level, regardless of unit specialty or designation. Informally, this suite of AM capability can be described as a general-purpose machine operated by a "general purpose" Marine (i.e., any MOS, not only trained fabricators). According to *MCO 4700.4*, the TACFAB is to be employed at the organizational level to "provide a basic capability to print parts, tools, and other items from a central repository, while also providing the ability to develop and employ rapid prototypes" (USMC, 2020, p.1-4). The explicitly stated "central repository" implies that the majority of parts print files will be accessed via network connectivity from a database of approved part designs, with some limited design capability being resident in the Marine designated as the unit's "AM specialist." The quality of design and capability of rapid prototyping will be highly dependent on the individual operator's interest level and personal investment in the technology, as these incidental AM operators will likely have limited training and lack a formal fabricator MOS.

Although it lacks a metal capability, TACFAB is included here as it underpins AM accessibility within the USMC and is the technology that most units will turn to first to solve a readiness issue. The TACFAB is the "first line of defense" for AM solutions and it should be assumed that if a part can be successfully printed at the organizational level in polymer, no demand for that part in metal will arise.

3. Expeditionary Fabrication Facility

The Expeditionary Fabrication Facility (XFAB) is the central system of interest to this thesis, as it is currently the only metal AM capability in the Marine Corps; this metal capability is a "hybrid 3D" process and is currently experimental only. The XFAB is the AM capability resident at intermediate-level maintenance facilities (listing of initial distribution plan is listed in Table 2). As defined in *MCO 4700.4*, "XFAB is a modular expandable shelter deployed in-concert with the Shop, Equipment, Machine Shop (SEMS) developed as an FY-19 POR. XFAB is designed to carry multiple types of AM systems and related tools and is staffed by trained machinists to reflect the fabrication capabilities resident within [intermediate maintenance activity] units" (USMC, 2020, p. 1-4). The article, *Expeditionary Fabrication in the Marine Corps,* further details the XFAB, stating,

> The current XFAB set consists of small, medium, and large polymer and blended-material printers, coupled with a large laser cutter, high-performance computers, and an assortment of small hand and post-processing finishing tools. XFAB's present modest capabilities are designed on a modular concept, to allow for future individual hardware and software upgrades without disrupting the system as a whole. Each module is defined by size, weight, and power limits so that printer and component upgrades do not exceed constraints imposed on the overall system. The 8-by-8-by-20-foot expandable shelter is hardwired to accommodate a future

> metal printing capability, and it is internet-enabled so users can access CAD files remotely and print from anyplace in the world. (Roach, 2021, para. 11)

General view photographs of the XFAB in expanded configuration are shown in Figures 1 and 2. The Marine Corps initially planned to field 21 XFABs to "supplement the supply chain and return combat-damaged equipment back to service" (Inspector General [IG], U.S. Department of Defense, 2019).

Figure 1. XFAB in Deployed/Operating Configuration. Note Environmental Control Equipment Connected to XFAB. Source: Roach (2021).

Figure 2. Second Image of XFAB in Deployed/Operating Configuration with Personnel Illustrating Relative Size of Facility. Source: Forsythe (2021).

D. METAL AM PROCESSES

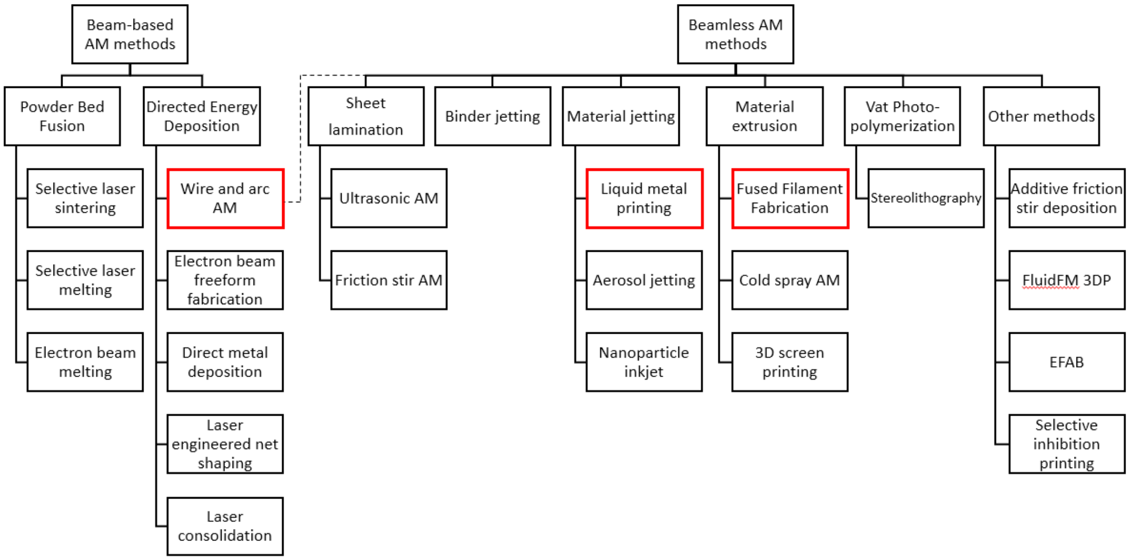
The XFAB system is expected to gain a metal AM capability in Fiscal Year 2025, with the exact process yet to be determined (M. Audette, personal communication, September 30, 2022). Several factors influence the selection of a metal AM process for expeditionary operations. These factors are what make the deployed context unique and distinct from stationary, lab-based metal systems suitable for use at the depot and installation levels. Broadly speaking, an expeditionary metal AM system should avoid or limit:

- excessive power consumption/requirements
- excessive physical dimensions or weight
- highly sensitive processes (i.e., sensitive to temperature, humidity, or vibration extremes)

- exotic raw materials that either require highly controlled storage or application, hazardous materials, or are difficult to locate outside of military or host nation supply chain

The raw material, or feedstock, for an expeditionary metal printer is ideally chemically stable (for shipment and long-term storage), easy to procure, easy to transport, and easy to manipulate via AM process into functional, useful, and durable final objects (with durable implying that it exceeds the durability of an identical polymer object). An example of feedstock unsuitability is the need for storage, transportation, and use of powdered metals for powder-bed fusion; this feedstock could easily be contaminated in austere environments. Additionally, handling powder metal requires additional safety considerations (Zelinski, 2019). Other consumables associated with printing which vary by process; examples of other consumables could be binder solution, debinding solvent, and/or shield gas.

Several of these broad attributes can quickly rule out some metal AM systems. Figure 3 shows a complete taxonomy of AM processes, not all of which are suitable for metal and/or expeditionary application. Some metal AM methods such as powder-bed fusion, powder-feed, or binder-jet-based methods require either “high-power laser and inert environments or extensive post-processing” (Ansell, 2021, p.2). Other processes shown in Figure 3 are unsuitable for expeditionary AM due to strict print environment conditions, feedstock sensitivity, equipment size, or hazardous material considerations. Requirements such as these are not practicable in an expeditionary environment, ruling out any process that uses them.



This figure is based on ISO/ASTM standard on AM terminology. Processes considered in this analysis are highlighted in red. Other processes depicted are unsuitable for expeditionary AM due to environmental control conditions, feedstock sensitivity, equipment size, or hazardous material considerations.

Figure 3. Taxonomy of Additive Manufacturing Techniques. Adapted from Ansell (2021).

The attributes that make a metal AM technique suitable for expeditionary use are further discussed and examined in this thesis. The following sections summarize four types of metal AM processes suitable to be considered for expeditionary operations and addition to XFAB. A summary of each process is shown in Table 2. Appendix A contains characteristic and performance data for each printer.

1. Hybrid Manufacturing / Wire Arc Additive Manufacturing

Hybrid manufacturing is a general term for a manufacturing method that combines an AM process with a subtractive manufacturing (SM) process to produce a finished part. Subtractive manufacturing is "making objects by removing of material (for example, milling, drilling, grinding, carving, etc.) from a bulk solid to leave a desired shape" (ASTM International, 2013, p. 2). While the SM component is typically a 5-axis computer numerical control (CNC) machine, any process by which material is removed from an additively manufactured object would fit the definition.

Metal hybrid manufacturing is an area in which the USMC has, an appreciable amount of experience, as this technology has been in use since 2018 (to include in a deployed environment) but has not been officially designated as a program of record. The ruggedized, mobile hybrid machines were used by the Marine Corps as part of the initial metal AM capability set, the Expeditionary Manufacturing unit, or "ExMan" (Zelinski, 2019). The hybrid system was developed by 3D Hybrid Solutions, Inc. and used the 3D Hybrid Add-on Wire-Arc tool (a wire arc AM process) with automatic tool changeover for rapid transition from AM to SM of the same part (Metal-AM.com, 2019). As shown in Figure 3, wire arc additive manufacturing (WAAM) is a variant of the larger group of directed energy deposition (DED) technologies. For the remainder of this thesis, DED and WAAM are used interchangeably, and any instances of DED specifically refer to the WAAM process. Figures 4 and 5 show the 3D Hybrid system in use in the ExMan.

Figure 4. 3D Hybrid Solutions Machine in the "ExMan" Unit. Source: Zelinski (2019).

The metal 3D printing head mounts onto an existing CNC milling machine in parallel with the metal cutting spindle. The resulting hybrid system can 3D-print features and machine those features to tolerance within the same setup. The operator needs to wear no special personal protective equipment beyond eye protection.

Figure 5. A 3D Hybrid Solutions, Inc. Machine Paired with a Tormach CNC machine in use in "ExMan." Source: Zelinski (2019).

Hybrid AM can accommodate a variety of metal AM methods, including laser melting of powder spray, wire arc, and cold spray, but the USMC's use of WAAM offers safety advantages as the feedstock is solid wire instead of powder and electrical current melts the wire rather than a laser (Zelinski, 2019). As described by the Additive Manufacturing Research Group of Loughborough University, DED generally consists of five steps:

1. A 4- or 5-axis arm with nozzle moves around a fixed object.
2. Material is deposited from the nozzle onto existing surfaces of the object.
3. Material is either provided in wire or powder form.
4. Material is melted using a laser, electron beam, or plasma arc upon deposition.
5. Further material is added layer by layer and solidified, creating or repairs new material features on the existing object (Additive Manufacturing Research Group [AMRG], n.d., para. 3).

In addition to safety advantages of wire feedstock, the use of common and economical materials also allows DED technology to offer quality, reliability, and cost benefits (Metal AM, 2019). A simplified image of the DED process is shown in Figure 6.

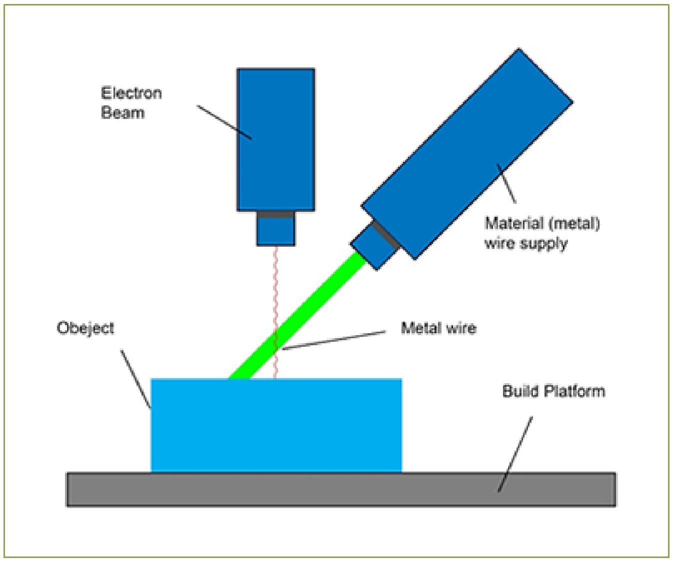


Figure 6. Simplified DED Process Image. Source: AMRG, (n.d.).

3D Hybrid Solutions, Inc. notes that an inherent benefit of hybrid manufacturing is the post-processing itself, as most “raw” AM parts lack acceptable finish quality or required dimensional precision to be a final, useful product, regardless of the AM process used. Thus, the CNC expense is inherent in metal AM and that “DED technologies ignore the goal of surface finish and precision, instead focus[ing] on speed and material quality. The CNC process provides the precision required” (3D Hybrid, n.d.).

The representative system considered in this analysis is the system as operated in the ExMan pilot system, consisting of a 3D Hybrid Solutions wire-arc DED printer and a Tormach CNC machine. Writer Beau Jackson, from an AM industry website titled 3D Printing Industry, noted that “3D-Hybrid’s tool heads are well-suited to part refurbishment and repair services” (2018, para. 7). In an interview, a representative from 3D Hybrid Solutions noted the following value propositions for consolidating an AM tool like the wire-arc deposition head with a CNC machine:

- In-process machining of parts in a single setup
- Simplified management structure and reduced learning curve
- Greatly reduced barrier to entry for metal AM
- Repair and salvage applications
- Just-in-time manufacturing, feeding wire to near-net-shape production
- Reduced material costs on large parts
- Multi-material part applications (Cole, J., 2018, para. 7)

The 3D Hybrid machine in use with the USMC "reportedly offers X-axis travel of 46cm (18 in), Y-Axis travel of 28cm (11 in), and Z-axis travel of 41cm (16.25 in), as well as a fourth axis for rotary build up and impeller fan applications. The Wire-Arc tool is said to offer build speeds upwards of 3.6kg/h (8 lb./h)" (Metal AM, 2019, para. 5). A summary of the pros and cons of hybrid manufacturing is listed in Table 2.

2. Liquid Metal

Liquid metal is a new technology developed in 2017, with first commercial availability in 2020 (Potter, 2017; Miller, 2021). Liquid metal printing involves the jetting of liquid (molten) metal into a solid, freeform shape without the use of a laser or electron beam (Ansell, 2021). Currently, two methods of liquid metal jet printing exist, "continuous jetting" and "drop on demand jet," distinguished by where in space the liquid metal stream breaks up in relation to the jetting orifice (Thirumangalath, n.d.). For "drop on demand," a metal wire is used as a material source and is fed into the machine, where it is melted in a ceramic nozzle; the resulting liquid metal is then expelled by a magnetic field in droplet form onto a movable build plate (Magnussen, 2022). Figure 7 shows a visual depiction of the two variations of drop on demand and continuous jetting.

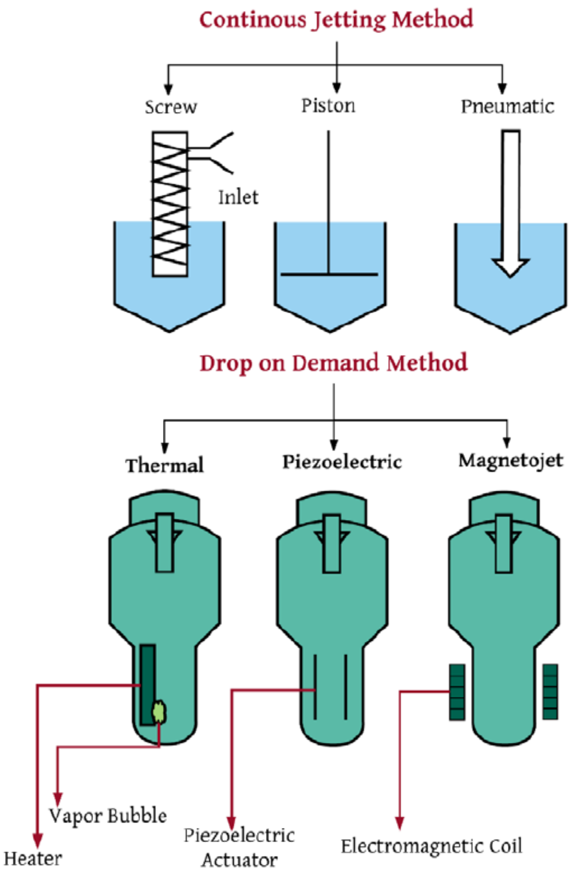
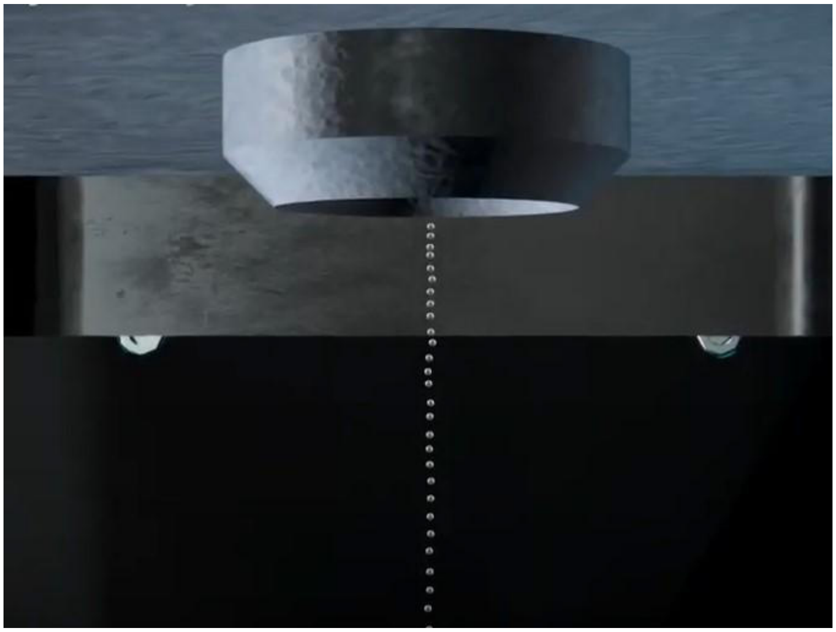


Figure 7. Continuous vs. Drop on Demand Liquid Metal 3D Printing Approaches. Source: Thirumangalath (n.d.).

The representative printer for this analysis is the Xerox ElemX Liquid Metal 3D Printer. The ElemX follows the "drop on demand" process as described previously, melting aluminum wire in a heated crucible at over 800°C and then depositing droplets via magnetic field onto a heated build plate (H., 2021). This process is faster than many other metal AM methods and requires less post-processing, with printed parts capable of immediate use after separation from the build plate (H., 2021). The use of aluminum in the ElemX offers a relatively cheap and common material with desirable strength properties in conjunction with corrosion and oxidation resistance (H., 2021). Figure 8 shows the liquid metal drops from the Xerox ElemX liquid metal printer.



After the ElemX melts aluminum wire, electromagnetic pulses around the outside of the melt pool “squeeze” the pulses back and forth, and individual drops of molten metal exit the nozzle at the rate of hundreds of drops per second.

Figure 8. Conceptual Image of Individual Drops of Molten Metal Exiting the Xerox ElemX printer. Source: Martin (2023).

Although still in relatively early development stages, liquid metal AM (LMAM) has the potential to solve several current AM developmental challenges (Ansell, 2021). Dr. Garth Hobson, a professor at the Naval Postgraduate School (NPS) and chair of the Department of Mechanical and Aerospace Engineering, noted that, “It takes literally minutes to have a part in your hand, versus other printers where it takes hours, or sometimes days, to get a part off the build plate” (Martin, 2023). Table 2 summarizes the pros and cons of liquid metal AM.

The U.S. Navy and Marine Corps have begun accruing an experience knowledge base with liquid metal printing through the NPS’s Cooperative Research Agreement with Xerox (Schehl, 2021; Magnussen, 2022). Figure 9 shows parts printed in aluminum 4008 at NPS. This partnership eventually resulted in the Xerox ElemX Liquid Metal 3D Printer being deployed on a Navy ship while underway during a large-scale joint exercise (Verger, 2022; Breeden, 2022). Figures 10 and 11 show the Xerox ElemX liquid metal printer containerized for transportation and employed onboard the USS ESSEX in a standard

8’x8’x20’ ISO container. The printer was operated inside the container while placed in the hangar deck of the USS ESSEX.

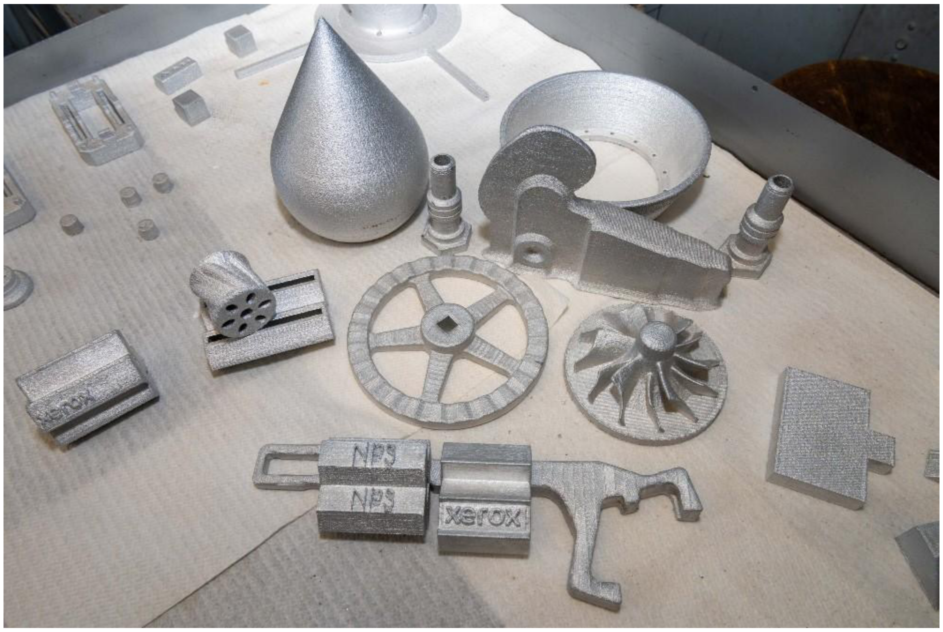


Figure 9. Aluminum Parts Printed at Naval Postgraduate School on the Xerox ElemX printer. Source: Martin (2023).

Figure 10. Xerox ElemX Liquid Metal 3D Printer Installed in an 8’ x 8’ x 20’ ISO Container for Use And Experimentation on USS ESSEX, July 2022. Source: Wakefield (2022).

Figure 11. Interior View of Xerox ElemX Liquid Metal 3D Printer Installed in an 8’ x 8’ x 20’ ISO Container for Use and Experimentation on USS ESSEX, July 2022. Source: Wakefield (2022).

3. Fused Deposition Modeling / Fused Filament Fabrication

Fused deposition modeling (FDM), sometimes also referred to as fused filament fabrication (FFF), is a popular process than has been very successful in application with polymer printers. The basic process originated with polymers and generally applies to metal in the same manner. In FFF, a heated nozzle extrudes a molten media (plastic, metal, etc.) and deposits it in thin layers on to a print bed; these accumulating layers eventually form a final part (Weiner, 2020). To produce the desired part, either the nozzle, the print bed, or both move while the media is being extruded (Weiner, 2020). FDM/FFF processes typical use two nozzles to print a part: the part filament and a support filament, also called a ceramic release material. The ceramic support is not an actual piece of the desired end part, but rather forms a scaffolding-like support structure in critical areas of the desired object as it is being printed. These support structures are of a weaker material than the part media and typically break away easily during post-processing. Figure 12 depicts how the two filaments work together to produce a stable part.

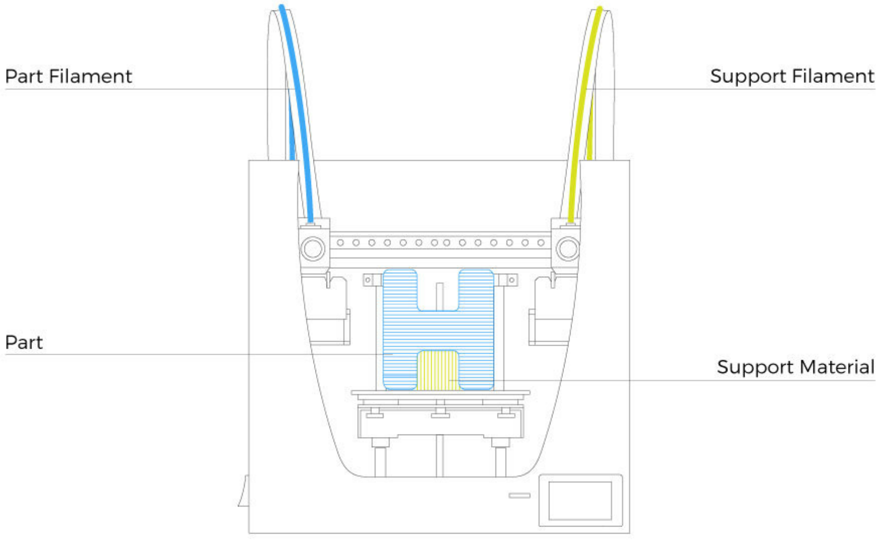
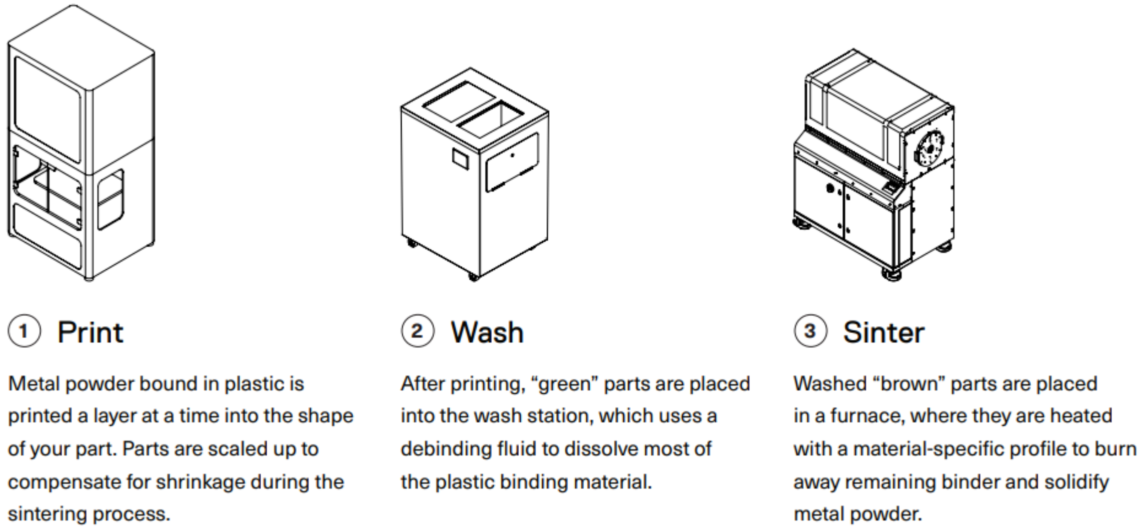


Figure 12. Depiction of Part Filament And Support Filaments in an FFF/FDM process. Source: BCN3D (2018).

The same basic principles of polymer FFF hold true when applied to metal but there are some extra considerations. According to the manufacturer Markforged, “metal FFF is a three-step process that uses bound powder feedstock made from metal injection molding media (metal powder bound together in waxy polymers),” and a “post-printing, high-energy process called sintering which turns printed parts fully into metal” (Markforged, n.d.a., p.7). Additionally, a metal FFF printer uses a vacuum-sealed print sheet instead of a conventional print bed (Markforged, n.d.b.). Figure 13 graphically depicts the three steps.



① **Print**

Metal powder bound in plastic is printed a layer at a time into the shape of your part. Parts are scaled up to compensate for shrinkage during the sintering process.

② **Wash**

After printing, “green” parts are placed into the wash station, which uses a debinding fluid to dissolve most of the plastic binding material.

③ **Sinter**

Washed “brown” parts are placed in a furnace, where they are heated with a material-specific profile to burn away remaining binder and solidify metal powder.

Figure 13. Three Step Process of Metal FFF. Source: Markforged (n.d.a.).

In a white paper on metal FFF, Markforged notes several design and operation considerations:

> - Metal FFF is not optimized for solid parts—typically, parts are printed with closed cell infill. Solid parts can be printed but increased solid part thickness exponentially impacts debinding time. Some metal FFF solutions forgo a solvent based debind and perform the entire debinding process in the sintering furnace. However, this approach adds time to the sintering process and limits the variety of parts that can be manufactured.
> - Metal FFF typically creates near net shape parts that do not hit precision machining tolerances. Parts can be post-processed to hit tight tolerances if needed. (Markforged, n.d.a., p. 8)

Markforged, while acknowledged as having some bias as a developer, offers an outlook and long-term view for FFF processes, noting that it is a rapidly maturing process with machines becoming more capable and reliable (n.d.a.). Markforged predicts that as the process continues to mature, metal FFF printers "will become a regular fixture in manufacturing facilities due to its affordability, accessibility, and versatility of manufacturing complex metal parts" (Markforged, n.d.a., p. 8).

The Markforged Metal X is included as the representative metal FFF system for this analysis. The Markforged Metal X has been identified as a good entry point for organizations to print end-use metal parts (Fisher-Wilson, 2019). Markforged describes the Metal X as "one of the most intuitive metal 3D printers available today," requiring no dedicated operator and minimal personal protective equipment (PPE) (Markforged, n.d.a.). The Metal X is capable of printing in stainless steel, tool steel, Inconel, and copper (Markforged, n.d.c.). Table 2 summarizes the pros and cons of liquid metal AM.

4. Bound Metal Deposition

The bound metal deposition (BMD) process is nearly identical to FFF/FDM, with the names often varying between manufacturers in attempts at differentiation in a booming market. BMD is an extrusion-based process that creates metal components through extrusion of a metal powder, thermoplastic media held together by both wax and a polymer binder (Proto3000, Inc., 2018). To print, the media is heated and extruded onto a build plate, layer by layer, forming a "green part," that requires a debinding process to remove the binder, and sintering to densify the metal particles (Proto3000, Inc., 2018). Sintering removes any remaining binder and fuses metal particles together, causing the part to densify up to 98%, comparable to cast parts (Desktop Metal, Inc., n.d.). The primary difference between FDM and BMD is that the metal filament used for printing in BMD has a much higher percentage of metal powder than the filament used with FDM (Bazinet, 2022).

The representative system discussed in this analysis is the "Studio System 2" from Desktop Metal, Inc. According to Desktop Metal literature, "the Studio System 2 features a two-step process the eliminates the need for solvents and uses materials that can be easily stored and handled – making it ideal for use in an office environment – no special facilities and no respiratory PPE needed. The only requirements are an internet connection, ventilation, and power…" (Desktop Metal Inc., n.d.). While the elimination of the solvent-based debinding process removes the stockage requirement for the solvent, debinding by sintering is found to be 6 to 10 times slower than solvent-based debinding (Markforged, n.d.a.). The Studio System 2's two-step process uses a separate machine for each step. Figure 14 shows an image of the Studio System 2, including printer (middle) and furnace (far right). A summary of the pros and cons of BDM is shown in Table 2.

Figure 14. Illustration Showing the Relative Size And Scale of the Desktop Metal Studio System 2. Source: Desktop Metal Inc. (n.d.).

5. Summary

This chapter examined the four candidate metal AM processes and highlighted the essential characteristics of each process that affect suitability for expeditionary employment. Each process offers unique advantages and disadvantages; the categorization of these attributes can be a fluid problem, as an advantage in one scenario could turn into a disadvantage in another. Additionally, many of the candidate processes have several pros in common with one another, such as commonly used materials (e.g., aluminum and steel), minimal PPE requirements, relatively low costs compared to other metal AM processes, and a physical size suitable for expeditionary transportation modes. These common advantageous traits directly influenced the inclusion of these particular four processes in the analysis. This is not to say that there are not other processes that offer similar advantages, but only that these four were felt to be sufficiently developed in their current state for formal adoption by the Marine Corps.

The equipment and process characteristics discussed in this section must be merged with the operational contexts discussed in Section A. As presented by the manufacturers, many of these systems are targeted at small- to medium-sized companies located in non-austere, civil areas with stable environments and robust infrastructure support. The four processes in this analysis are expected to reliably operate in conditions opposite from those just described. An ideal metal AM system may be an unacceptable solution when placed in a certain operational context; thus, an objective to consider is a process that retains its utility in the widest variety of operational scenarios.

The unique advantages and disadvantages of each process present a traditional trade-off analysis problem, as some advantages (e.g., liquid metal's high cycle time) can come with an attached cost (design limitations due to droplet method). This balance of advantages and disadvantages is present in all four processes examined. Table 2 captures the most unique pros and cons between alternatives, compared against one another only and not against systems outside the scope of this analysis.

Table 2. Summary of AM Process Pros/Cons

AM Process	Pros	Cons
Hybrid AM (3D Hybrid Solutions)	Accepts multiple AM processes Simple consumables (wire feedstock and shield gas) Higher-quality surface finishes and more precise dimensions with SM	Two-step process adds production time Combination of processes into single machine occupies machine for entirety of production time

AM Process	Pros	Cons
Liquid Metal (Xerox ElemX)	High cycle times (Magnussen, 2022) No or optional post-processing requirements (Wakefield, 2022) Low part cost (Magnussen, 2022) May allow for printing of non-weldable metals/metal alloys (Ansell, 2021) Potential for use of recycled metal (Ansell, 2021)	Limited build volume (Magnussen, 2022) Part design limitations due to droplet style of printing (Magnussen, 2022) New technology with limited testing (Magnussen, 2022) Large external dimensions of equipment High equipment cost relative to other processes
FFF (Markforged Metal X)	Lower investment to own and operate (Markforged, n.d.a.) Capable of bulk sintering process (Markforged, n.d.a.)	Post-processing required Requirement to stock debinding solvent Sintering/wash equipment adds weight & cubic footage Sintering requires high environmental precision and control (Markforged, n.d.a.)
BDM (Desktop Metal Studio System 2)	Applicable to sinter-able powders (e.g., steels, copper, and other metallic alloys) (Proto3000, Inc., 2018) Debinding and sintering combined into a single step (Desktop Metal, Inc., n.d.),	Post-processing required Elimination of debinding wash adds additional sintering time (Markforged, n.d.a.) Sintering equipment adds weight & cubic footage Sintering requires high environmental precision and control (Markforged, n.d.a.)

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III. LITERATURE REVIEW

As AM has expanded in capability, a significant amount of research has been dedicated toward evaluating the potential applications and utility of AM for military contexts. As this issue touches the entirety of the Department of Defense (DOD), the breadth of research is vast, with 139 theses written at NPS alone from 2010 to 2022, covering topics from medical logistics in operational environments to ship component risk mitigation on the Zumwalt-class destroyer (Williams, 2020; Wang & Whitworth, 2016). A 2019 Department of Defense Inspector General report, *Audit of the DOD's Use of Additive Manufacturing for Sustainment Parts*, found that "at least 81 Military Service depots, maintenance facilities, and field locations have used AM to produce thousands of AM parts and tools, such as cooling ducts, clips, and wrenches, to decrease maintenance time, reduce the impact of obsolete parts that are no longer available through traditional manufacturing sources, and improve existing parts" (IG, DOD, 2019, p. i). Because polymer is easier to work with and cheaper (resulting in lower barriers to entry), it has been on the forefront of analysis for the DOD's AM adoption efforts. As the ability to feasibly employ metal AM in an expeditionary environment is still a relatively recent development, rather little literature exists that examines the employment of such a technology. With TACFAB and XFAB systems both having polymer capability already, the official addition of a metal capability to XFAB is a significant step forward for the Marine Corps and requires research to ensure the appropriate technology is chosen for adoption, implementation, and employment. This section reviews existing literature related to the expeditionary employment of AM technology and examines the research related to metal AM in an expeditionary environment.

A. AM IN EXPEDITIONARY ENVIRONMENTS

In 2013, a report developed for the U.S. Army's Rapid Equipping Force to promote military-relevant AM applications recommended differentiating AM by technology and application and outlining unique considerations for AM in tactical environments (Lein, 2019). This section uses these two recommendations to identify attributes of AM technologies relevant to expeditionary employment and establishes employment considerations to assist in the cost effectiveness analysis of a metal AM printer.

This section examines literature regarding expeditionary employment for all types of AM, without focusing on a particular process or material. Section 1 reviews the DOD's guidance for expeditionary use of AM. Section 2 reviews desirable system attributes or specific properties needed in an AM system to be suitable for expeditionary operations. Section 3 reviews proposed employment models for AM systems.

1. DOD-level Guidance

The use of AM technology to support various military requirements within the continental United States has been well examined, with positive conclusions from research emphasized by the Joint Defense Manufacturing Council's publication of the *Department of Defense Additive Manufacturing Strategy* in 2021. This document establishes five goals and focus areas for the DOD regarding AM:

1. Integrate AM into DOD and the defense industrial base
2. Align AM activities across the DOD and with external partners
3. Advance and promote agile use of AM
4. Expand proficiency in AM: learn, practice, and share knowledge
5. Secure the AM workflow (Joint Defense Manufacturing Council [JDMC], 2021, p. 7)

While it is acknowledged that this document will naturally focus on a high-level overview, it is nevertheless worth noting that only a single sub-goal (out of 17 total sub-goals) is oriented on the expeditionary employment of AM in an expeditionary environment. This goal, titled, "Support forward deployment and application of AM in the field," covers the use of virtual environments to create digital twins and the importance of AM data security (JDMC, 2021, p. 13). Guidance relevant to each service's implementation of AM emphasizes the need to provide field units with the procedural framework to minimize the risk of using 3D printed parts, as well as the need for further development of facility, safety, and hazard risk assessment standards (JDMC, 2021). Of particular relevance is the note that the "expeditionary use of AM will take into consideration logistics for materials, machines, and personnel" (JDMC, 2021, p. 14).

Predating the higher DOD guidance, the 2017 *Department of the Navy (DON) Additive Manufacturing (AM) Implementation Plan V2.0* identifies five implementation strategies, with Objective 5, "Enable manufacturing agility through low volume production in maintenance and operational environments," directly addressing expeditionary employment of AM (Department of the Navy [DON], 2017). The DON defines the objective as such:

> In order to fully realize the potential of AM to shorten the logistics tail, the technology needs to move outside of laboratories and depots to be employed close to the point of need: afloat, subsurface, expeditionary, forward deployed, etc. In doing so, equipment is exposed to a number of environmental conditions that must be considered. This Objective encapsulate all the considerations necessary to ensure reliable production in any operational environment. (DON, 2017, p. 12)

The end state is listed as, "the ability to use AM to manufacture needed items in any location" (DON, 2017, p. 12). Additionally, five subordinate objectives are identified, shown in Table 3.

Table 3. Department of the Navy Goals for Manufacturing in Operational Environments. Source: DON (2017).

Focus Area	Project Description
5.2 Manufacturing in Operational Environments	5.2.1 Determine candidate components for manufacturing in operational environments
	5.2.2 Develop sensor package to study operational environments and deploy with targets of opportunity (fab labs, etc.)
	5.2.3 Develop ability to cost effectively replicate operational environments
	5.2.4 Determine candidate platforms for integration and perform integration studies
	5.2.5 Determine operational environment effects on material properties, processes, and procedure qualification

Despite dating to 2017 and being achieved in several areas, these objectives and end states, remain viable and useful guiding principles when assessing metal AM technologies for adoption.

2. System Attributes

Written in 2017, Daugherty's and Heiple's master's thesis, *Additive Manufacturing Solutions in the USMC*, contained a cost benefit analysis to examine the relative strengths and weaknesses of obtaining parts through OEM suppliers versus various methods of AM. Their results showed a cost advantage for continuous liquid interface production (CLIP), but the analysis focused exclusively on polymer manufacturing. A 2015 qualitative analysis recommended adoption of FDM or selective laser sintering (SLS) technology; this recommendation was influenced by the unavailability of suitable metal AM processes, and SLS was included as it was the only feasible process capable of printing in metal (McLearen, 2015).

In establishing the background for their research, Daugherty and Heiple uncovered several issues with AM when considering deployability. First, the need for constant network access was discussed as a potentially prohibitive requirement as network access, while a high operational priority, cannot be guaranteed in all scenarios (Daugherty & Heiple, 2017). Secondly, sensitivity of feedstock or binder materials could limit deployability of a machine, as keeping raw materials stocked and stable in an austere environment could present an additional logistical challenge (Daugherty & Heiple, 2017). Thirdly, strict machine setup and operating requirements (e.g., leveling of the machine) could impair the functionality of the machine and negatively affect print capability or quality (Daugherty & Heiple, 2017).

After conducting a CBA on two different polymer printers, Daugherty and Heiple conclude their research by noting that several "intangibles" play a critical role in evaluating one technology over another. The factors discussed include the "durability and deployability and their respective print materials;" physical levelling requirements for machines in forward deployed locations; print speed, which is said to have the "most drastic impact on net present value" (NPV); and the size of printers, especially "when considering the current housing of the EXMAN and EXFAB trailers" (Daugherty & Heiple, 2017, p. 82-83).

Norako notes that the current constraint facing the Marine Corps' AM capabilities is not the TACFAB or XFAB employment concepts, but rather the individual machines inside the XFAB (a result of an analysis identifying poor expeditionary suitability of some printers) (2021). Printer attributes associated with deficient performance were sensitivity to harsh environments, unprotected electronics and climate control mechanisms, non-modular designs, and inability to handle varying quality of power supply (Norako, 2021).

Roach (2021) neatly summarizes the challenge associated with expeditionary additive manufacturing specific to the XFAB, arguing that:

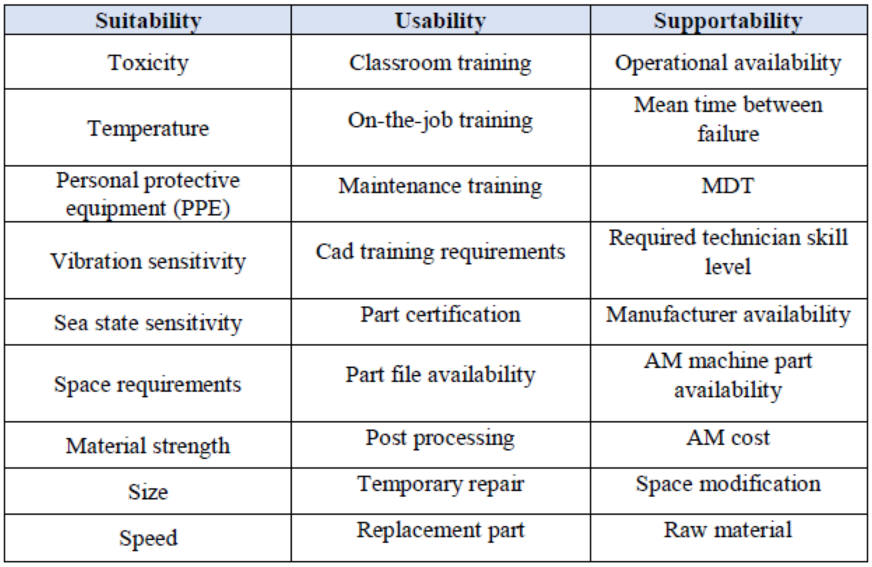
> The primary technical challenge for XFAB is integrating a complete set of additive manufacturing equipment into an expandable, rigid-wall, deployable shelter. AM printers are typically used in carefully crafted, temperature-controlled spaces, because 3D printers are notoriously sensitive to temperature, humidity, shock, vibration, and unconditioned power. (Unconditioned power can fluctuate in voltage and is susceptible to electromagnetic interference from nearby equipment.) If larger parts are desired, then larger, heavier printers (and, in XFAB's case, a laser cutter for post-processing) are needed but not always easily integrated into the constraints of a steel shelter. XFAB's key performance requirement, however, mandates production of functional parts far from strictly controlled professional laboratory environments. (para. 10)

Roach also describes the potential, revolutionary supply chain benefits offered by expeditionary metal AM. He highlights the ability to rapidly produce unique replacement parts and prototypes at the point of demand while minimizing storage requirements, waste, costs, and risk to vulnerable transportation assets (Roach, 2021). The speed at which parts are produced is mentioned to be relevant to tactical outcomes on the battlefield (Roach, 2021). However, the effect of improved print speed on 3D printer value has been found to have limitations and is subject to the law of diminishing returns, implying that there is a point at which the cost of increasing print speed no longer provides sufficient benefits to justify the expense (Song & Zhang, 2020).

A thorough master's capstone project, "Navy Additive Manufacturing Afloat Capability Analysis," written by Banks et al. (2020), used a systems engineering approach to identify the best types of AM equipment for U.S. Navy use, determine optimal AM deployment order, and present a benefit-maximizing dispersion plan. Their research offers an in-depth review of attributes that make AM equipment well-suited for expeditionary employment aboard Navy ships, which can differ somewhat from USMC expeditionary employment. Banks et al. note the ship-board environmental challenges of corrosive sea air, sea state (calm or rough seas), humidity levels, and constant vibration from ship's equipment (Banks et al., 2020). USMC expeditionary environments are subject to corrosive conditions and varying humidity levels but do not experience sea state or vibration effects (excluding instances of USMC printers operated on Navy amphibious shipping). Ship-board employment of AM systems does potentially allow for better AM environmental control (air conditioning, dehumidification, stable power supply) depending on machine placement on the ship and installation of environmental controls. The XFAB container does offer similar environmental control, but the tactical situation can influence the practicality and effectiveness of these systems (e.g., an erratic host nation power supply), whereas a ship-board system can offer more consistent control.

Their research produced the "Additive Manufacturing Research" (AMAR) Tool, an Excel-based heuristic tool that filters AM equipment based on user requirements (Banks et al., 2020). To reduce the effort to produce recommendations, the AMAR Tool first filters printers by "material type, non-flammability, technology, build volume, overall footprint, and power consumption" (Banks et al., 2020, p.58). After the first round of screening, the second selection process determines which AM machine would be the most beneficial, through the lens of three "-ilities" of suitability, usability, and supportability (Banks, 2020). The details of each of these "-ilities" is shown in Table 4.

Table 4. AM Equipment Attributes from the Additive Manufacturing Research Tool. Source: Banks et al. (2020)



Suitability	Usability	Supportability
Toxicity	Classroom training	Operational availability
Temperature	On-the-job training	Mean time between failure
Personal protective equipment (PPE)	Maintenance training	MDT
Vibration sensitivity	Cad training requirements	Required technician skill level
Sea state sensitivity	Part certification	Manufacturer availability
Space requirements	Part file availability	AM machine part availability
Material strength	Post processing	AM cost
Size	Temporary repair	Space modification
Speed	Replacement part	Raw material

These attributes were influenced in part by Naval Sea Systems Command's *Guidance on the Use of Additive Manufacturing* (2018), which identified the considerations for AM process suitability shown in Table 5.

Table 5. AM Process Suitability and Key Material Characteristics. Source: Naval Sea Systems Command (2018).

AM Process Suitability Considerations	Key Material Characteristics of an AM part
Geometric constraints Build volume Part size Surface finish Mating surfaces / interfaces Internal geometries Post-processing requirements	Strength Toughness Physical properties Frictional properties Fatigue strength, crack initiation, and growth Creep and stress relaxation Corrosion resistance Joining, including weldability and ability to be brazed Fire / smoke / toxicity requirements Environmental requirements – light, temperature, and humidity Inspectability Sealing requirements Chemical compatibility

A 2021 master's capstone project built a similar decision tool to facilitate AM machine selection for expeditionary employment based on user-selected criteria. The "Navy Expeditionary Additive Manufacturing (NEAM) Capability Integration" report's objective was to guide decision makers in AM printer selection in the context of distributed, expeditionary advanced base operations by the Naval Expeditionary Combat Command (NECC) (Amodeo et al., 2021). The NECC is a U.S. Navy force comprised of a variety of force-provider and enabling capabilities, one of which is the Naval Construction Force (NCF), or Seabees. The NCF offers a robust construction capability and can be expected to operate in expeditionary conditions similar to Marine Corps forces. The inclusion of the NECC in the AM decision-making process provides a valuable link to USMC interests.

The tool produced through their project was called the Additive Manufacturing Process and Analysis Tool (AMPAT) and used user-specified parameters such a machine failure rate, operational availability, and environmental conditions to generate a filtered and ranked database output of AM systems that meet the user's requirements (Amodeo et al., 2021). As part of their analysis, Amodeo et al. highlighted the importance of a post-processing to producing a reliable and operationally relevant part and briefly discussed the ExMan facility, noting the hybrid AM equipment, simplicity of use, and minimal training requirements (Amodeo et al., 2021).

Amodeo et al. followed a deliberate systems engineering process in creating the AMPAT tool. As part of this process, stakeholder needs were evaluated and many of the needs parallel USMC needs for AM capabilities. Similar needs included: production of replacement parts; the ability to surge significant AM capacity and capability to support major combat operations; and the production of temporary-use or "bridge solutions" when the supply chain is unable to meet demand or required delivery times (Amodeo et al., 2021).

Additionally, through the requirements analysis process, the research team defined specific parameters for inclusion in AMPAT. These parameters were identified through literature review, subject matter expert interviews, and stakeholder input. Figure 15 graphically shows top areas of concern from each of those three sources.

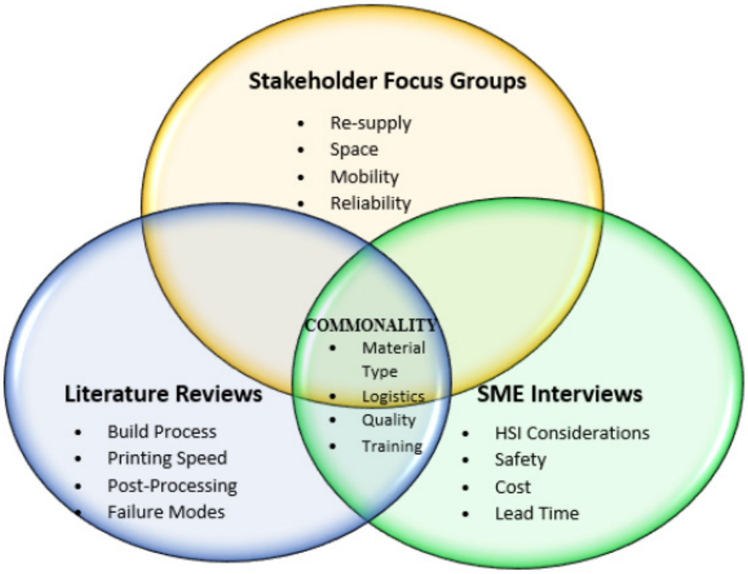


Figure 15. Significant Parameters for Expeditionary AM Systems. Source: Amodeo et al., (2021)

Ultimately, the research team identified 44 measurable parameters across three top level functions and 7 subfunctions for inclusion in the AMPAT tool (Amodeo et al., 2021). Monetary cost was a factor in 7 of the 44 measurable parameters: initial spares and inventory cost; personnel training cost; distribution and transportation cost; unscheduled maintenance cost; component cost; material cost per pound; and consumable cost per 100 hours of operation (Amodeo et al., 2021). Print times were not listed as included in the parameters, although post-processing time requirements were.

Acquisition cost or cost of the complete AM system (printer and post-processing equipment) was not shown as included in the parameters. This is explained by Amodeo et al. as a limitation of the analysis, noting that AMPAT must be combined with additional studies (specifically cost analysis and analysis of alternatives studies) to produce the best results (Amodeo et al., 2021).

3. Employment Models

In 2014 an exploratory study was conducted by R. Appleton titled, “Additive Manufacturing Overview for the United States Marine Corps,” which describes known problems with inventory, transportation, and obsolescence affecting deployed forces, as well as AM's role in providing a solution. While the obsolescence discussion focused on depot-level, CONUS-based AM facilities, the other two problems were more expeditionary in nature. Limited physical space on ship or on shore for part inventory could be solved by "storing files and raw materials, not parts" (Appleton, 2014, p. 24). This same idea was identified in 2015 by Sean Walsh in an article titled, "3D Printing—Enhancing Expeditionary Logistics," where he noted that feedstock would still need to be taken, but the total material stored could be reduced as many different parts could be made from the same raw material. Appleton described the transportation problem as significant delays and costs associated with delivery of high-priority items to remote areas, with the recommended solution to send "electrons, not parts" (2014, p. 24). Appleton's final conclusions emphasized the importance of a concept of operations for AM employment and that "a rigorous Business Case Analysis (BCA) must be conducted to demonstrate the overall value of the effort" (Appleton, 2014, p. 26).

Daugherty and Heiple uncovered a useful ConOps at the time of their research in 2017, when they interviewed numerous Marines assigned to the Marine Corps' 1st Maintenance Battalion. This battalion had experience with the Expeditionary Manufacturing Trailer (ExMan), the first experimental, proof-of-concept AM tool fielded by the Marine Corps. Through discussions with a sitting commanding officer of a Marine Corps Maintenance Battalion, a potential employment methodology for AM was discussed. This proposed vision "echelon [ed] printers in nodes by capability, utilizing the same structure as maintenance equipment" (Daugherty & Heiple, 2017, p. 29-30). This vision is akin to a layered, escalating, "defense in depth," of AM systems, allowing a deployed force access to increasingly capable AM capabilities as requests are moved further away from the forward edge of the battle area.

The first echelon, the organizational level, consists of far-forward combat and support forces, such as infantry battalions and combat logistics battalions (CLBs). These units "would only possess a desktop 3D printer. This would afford the capability of printing ABS [acrylonitrile butadiene styrene] remotely without assistance from higher commands" (Daugherty and Heiple, 2017, p. 29). The units at the next level (intermediate level), would possess more robust maintenance capabilities, such as the SEMS, multi-material printers, and scanners, while the highest level (depot level) would maintain larger and less mobile printers to enable printing in metal (Daugherty & Heiple, 2017). Benefits to this progressive methodology are cited as lessening the total requirement for assets and providing more flexibility (Daugherty & Heiple, 2017). This concept is also applied to part design as well, with lower levels only utilizing pre-prepared print files commensurate with their printer capability; if the print file is not pre-existing or cannot be printed on their machines (i.e., due to material or size constraints), the print request would be escalated to the next maintenance level (Daugherty & Heiple, 2017). This concept achieves maximum access to AM while minimizing overall acquisition cost, as fewer costly (but more capable) systems such as XFAB are required. A downside to this approach could be experienced when units are highly distributed in complex terrain (e.g., island chains), where the nearest higher level of AM capability beyond TACFAB is hundreds of miles away from the point of need. In this instance, some of the value of AM to reduce transportation burdens is diminished, though the overall customer wait time from initiation to part receipt is still likely to be less than the traditional supply system.

McLearen initially addressed this "defense in depth" concept for AM in a 2015 master's thesis, where he found that the Marine Expeditionary Unit (MEU) would benefit most from AM capabilities, with the larger Marine Expeditionary Brigade (MEB) benefiting next (p. 91). A standard MEU deploys with a CLB, while a MEB has a less-defined structure and has its capabilities tailored to the mission; a MEB could deploy with an intermediate maintenance capability (including robust AM capabilities as identified by the 1st Maintenance Battalion concept). A 2016 master's thesis examined AM in expeditionary operations and determined a significant return on investment for AM utilization (Friedell, 2016). Friedell researched several aspects of AM, with one research question examining what types of scenarios and use cases would benefit most from AM. One use case identified was "when a part is needed in a remote or austere environment such as onboard a ship or at a distant forward operating base, printing the much-needed part may be the only or least costly option available" (Friedell, 2016, p. 101). Additionally, Friedell found that "expeditionary manufacturing laboratories consist of AM machines but also include CNC, milling, and injection molding," and would "cut logistics lines, saving time, fuel, and lives in the process" (2016, p. 101).

In 2019 a paper titled "Networked Logistics and Additive Manufacturing," was presented at the annual Acquisition Research Symposium hosted at the Naval Postgraduate School. This paper by S. Sanchez, C. Luhrs, and M. McDonald, built upon a master's thesis by G. Lynch titled, *Networked Logistics: Turning the Iron Mountain into an Iron Network.* Using a simulation model, Lynch's thesis determines that there are significant operational benefits to replacing the Iron Mountain with a distributed network of mobile logistics support nodes including a "79% faster response time while using 22% less vehicles and leaving 94% fewer requests unfulfilled" (Lynch, 2019, p. v). However, Lynch notes that specific enablers are required to make the Iron Network possible, and that AM is one of these enablers: "additive manufacturing has the potential to dramatically improve the ability to acquire and distribute parts and supplies in an austere environment" (Lynch, 2019, p. 49).

The authors of *Networked Logistics and Additive Manufacturing* build upon this idea and state that additive manufacturing "has the potential to fundamentally change how military expeditionary operations are conducted" (Sanchez et al., 2019, p. 565). This central claim is expanded with a list of potential expeditionary AM benefits, including higher levels of readiness, lower costs, reduced logistics footprint, and reduced waste (Sanchez et al., 2019). Sanchez et al. warn that if suitability and reliability are not included in the decision-making process, "AM may end up being a costly and largely redundant logistics system running in parallel with the current supply chain, rather than being a transformative capability (2019, p. 566).

While many analyses identify the role AM can play as a source of supply, the First Marine Expeditionary Force (I MEF) AM policy letter, dated February 2018, specifically states that "AM is not an additional source of supply; however, it is a means to improve maintenance cycle time through production at the point of need (I Marine Expeditionary Force [MEF], 2018, p. 1). While the order was an interim solution and will likely require updating given progress in AM adoption, it is worth noting this viewpoint as it is contrary to one of the identified primary benefits of AM. The source of this position is likely to prevent AM circumventing the CONUS-based supply system while also avoiding unnecessary overreliance on AM, resulting in the AM machines not being used for truly time-sensitive or operationally critical parts. The importance of prioritization of request parts is an important operational employment consideration to account for.

AM as a source of supply has varying perspectives depending on the operational context. Song and Zhang (2020) wrote an analysis of the choice to "stock or print" from the context of a manufacturer entering emerging markets with minimum local supply support, which closely resembles military operations. Song and Zhang found that the optimal utilization of a 3D printer increases as part variety increases, and decreases as part criticality increases, "suggesting the value of 3D technology in tolerating large part variety and the value of inventory for critical parts" (2020, p. 1). In essence, this analysis finds optimum utility in using AM when part variety is large and finds value in holding inventory for critical parts to provide immediate availability (Song & Zhang, 2020). This conclusion is worth noting as it is counter to anecdotal intuition, which often argues that a significant benefit offered by AM is the immediacy of parts availability. However, the context for Song & Zhang's work does not factor in the military vulnerabilities and limitations associated with maintaining a large on-hand stock of critical parts. This difference in civil and military contexts introduces a significant, new variable to the analysis which makes Song and Zhang's conclusion less definitive.

In a 2021 master's thesis, Norako identified two specific opportunities suited for AM but that were not being pursued by the Marine Corps to the fullest extent: Humanitarian and Disaster Relief (HADR) operations and the potential for AM Operations Inside the Chinese weapons engagement zone (WEZ). For HADR, AM was posited to offer increase responsiveness and flexibility, with the non-combat environment of HADR operations allowing the XFAB and TACFAB systems at optimal locations to enable increased mobility, diminished supply line requirements, and longer operational endurance (Norako, 2021). The opportunity for employment of AM inside the WEZ offers a mitigating asset against the Chinese precision-strike missile threat, which threatens supply and logistics lines. Although AM cannot mitigate supply issues for Classes I (food/water), III (petroleum, oils, lubricants), and V (ammunition), Classes VIII (medical supplies) and

IX (repair parts) can be somewhat hardened (Norako, 2021). Norako notes that if a more expensive Class VIII or IX item could be printed, the Chinese would not have the ability to destroy those items while in transit, and also the U.S. would realize a reduction in transportation costs (2021). Additionally, the transfer of demand from Class VIII or IX parts to raw materials offers advantages, as the raw material can be sourced from a variety of suppliers and locations, offering greater concealment for the materials (Norako, 2021). This increase in concealment and additional avenues of supply could help ensure the raw materials make it to the point of production, ensuring the true critical item needed makes it to the intended user.

B. METAL AM IN AN EXPEDITIONARY ENVIRONMENT

This section covers previous research that examines the suitability and utility of specifically metal AM systems for military usage, strictly in an expeditionary environment.

As small-scale metal AM is a relatively new technology, scholarly research specifically focused on metal AM technology in an expeditionary environment is still a cutting-edge, developing area of research. In 2019 the U.S. Air Force sponsored an article written by Strong et al. through the National Center for Defense Manufacturing and Machining. The article, "Rethinking reverse logistics: role of additive manufacturing technology in metal remanufacturing," examined the repair of damaged industrial equipment via metal AM. Strong et al., note challenges for small and medium enterprises in acquiring metal AM systems due to cost, but stated that advancements in DED capabilities and adaptability for integration with traditional machines showed promise (2019). The Marine Corps' investment and use appetite most closely resembles a small to medium enterprise, which faces challenges due to lack of capital and expertise to adopt the new technologies (Strong et al., 2019). Although the Marine Corps has access to significant capital, the allocation decisions regarding that capital are the constraints which aligns the Marine Corps with the small and medium enterprises.

An emerging application of metal AM is maintenance and repair, with additional scenarios such as low production volumes, high material cost, and high machining costs are also seen as favorable for metal AM (Strong et al., 2019). The repair and low-volume production scenarios almost perfectly align with the Marine Corps expeditionary use case. To that point, Strong et al., note that the defense industry is unique among other industries for its focus on AM remanufacturing, particularly in production of both high-cost and end-use parts (2019). However, Strong et al.'s analysis remained focused on CONUS-based application of metal AM.

Strong et al., choose to focus on DED as a metal AM technology, stating "integrating DED with conventional processes such as machining and grinding into Hybrid AM is well suited for remanufacturing of metal parts" (Strong, 2019, p. 1). Further justification of DED is provided: "The one disadvantage to metal AM processing is that current AM methods produce parts with poorer surface finish and part accuracy. A solution to this issue is to successfully integrate AM and machining through a hybrid approach which would combine the discrete advantages of both approaches" (Strong. et al., 2019, p. 3).

In 2019, writer Peter Zelinski covered the Marine Corps' ExMan facility and use of hybrid 3D technology. Zelinski states that the Marines Corps sought metal AM operation in conjunction with CNC machining, for "the sake of truly obtaining the part as fast as possible" (2019, para. 4). Zelinski (2019) found that the perceived utility and applications of metal AM included part making, tool making, and a resource for repair, and highly depended on the perspective of the employing personnel and the situation at hand. The DED process in the ExMan's hybrid AM system is said to be a resource not just for production of new parts, but also repairing or modifying existing components (Zelinski, 2019). The repair and modification capabilities are achieved through DED's ability to add metal onto existing parts, with the existing part used as the starting work surface.

The U.S. Navy has been actively placing 3D printers on ships for several years and has now begun aggressively pursuing the addition of metal printers on ships. Two variations of metal AM, the Xerox ElemX liquid metal and the Phillips Hybrid Additive Manufacturing System, were deployed on two different amphibious (LHD class) ships in 2022 (Lundquist, 2023). The ElemX was part of a temporary experimentation effort between the U.S. Navy, NPS, and Xerox, while the Phillips machine was intended for permanent installation (Lundquist, 2023). The use of metal AM on board ship presents numerous challenges including temperature, vibration, humidity, sea state conditions, and a saltwater (corrosive) environment. Additionally, the application of these printers on amphibious class shipping is a significant benefit for the Marine Corps, as these ships are designed for transportation and support of Marine Corps equipment and aircraft and, as such, will be in a position to support both the ship and the embarked Marine forces.

IV. METHOD

This chapter describes the cost effectiveness analysis method used to assess each candidate process, challenges encountered during the analysis, and assumptions used to facilitate the analysis. The rationale for use of a cost effectiveness analysis rather than a cost-benefit analysis and the difficulty of monetizing benefits is also addressed.

A. COST EFFECTIVENESS ANALYSIS

A cost effectiveness analysis (CEA) is used to quantify the utility and potential benefits of the metal AM processes under consideration. According to Cellini and Kee as published in the *Handbook of Practical Program Evaluation* (2010), a cost-effectiveness analysis "seeks to identify and place dollars on the costs of a program" while a cost-benefit analysis (CBA) attempts to "compare costs with the dollar value of all (or most) of a program's many benefits" (p. 493). A CEA was chosen as metal AM systems in an expeditionary context are not acquired or operated specifically to produce a monetary or societal benefit, thus making monetization of impacts (and estimation of net benefits) difficult. The primary purpose of metal AM systems in an expeditionary context is to sustain a combat force and enable continued military operations, and benefits are difficult to quantify. While there may be broad positive externalities from the operation of metal AM, such as winning a battle or relieving human suffering, they are outside the scope of this thesis. Boardman et al. note that if "not all of the impacts can be monetized, it is not possible to estimate net benefits" (Boardman et al., 2018, p. 43).

In situations where a net benefit cannot be estimated, analysts can use the non-monetized, quantitative benefit and the total dollar costs to develop a cost-effectiveness ratio that enables the ranking of alternatives in terms of the cost-effective criterion (Boardman et al., 2018). As published in the *Handbook of Practical Program Evaluation*, Cellini and Kee (2010) note that a CEA is most useful when comparing multiple alternatives against a known, desired outcome to determine which option achieves the greatest outcome for the cost, and when major outcomes are "either intangible or otherwise difficult to monetize" (p. 496). A major difficulty noted with a CEA is that it does not provide a monetized value of benefit for the analysis' output, leaving the benefits open to subjective judgment (Cellini & Kee, 2010). This subjective judgment, however, is often an important element in military contexts due to the difficulty in benefit monetization and complexity and possible consequences of operational decisions. A CBA is known to be difficult and time consuming, with a CEA providing a "good starting point by requiring the evaluator to identify the most important outcome and relate that outcome to the dollars spent on the project" (Cellini & Kee, 2010, p. 496).

As an example of the difficulty of benefit monetization, if a forward EAB is operating with a single forklift, that forklift becomes a critical piece of equipment for completion of sustainment functions by that EAB. If a single bracket on that forklift fails and causes the forklift to become incapable of handling material, the EAB becomes unable to complete required sustainment missions. The single bracket may cost a trivial amount to manufacture, and the metal AM system may cost a significant amount, but the military necessity and benefit of that bracket would be very difficult to monetize, with a multitude of factors influencing benefit calculation. Also, it can be difficult to predict on which occasions the bracket would be considered a critical element failure rather than a routine inconvenience. In a CBA-type analysis, the cost might be higher for the USMC to own metal AM machines and print an individual part, but the criticality of that part in a combat environment can likely compensate for the higher individual part cost. Thus, the cost effectiveness of the metal AM system is a more valuable analysis. The rationale for a CEA is most succinctly explained by the concept of balancing effectiveness versus efficiency. Metal AM in an expeditionary context is not existing for an overall economic efficiency benefit, but rather to ensure the mission effectiveness of a deployed force.

As the specific metal AM systems have not been selected, this CEA is being conducted *ex ante*, which is useful when comparing alternative prospective programs (Cellini & Kee, 2010). Cellini and Kee note that an *ex-ante* analysis often requires a significant number of assumptions and may be less accurate, as estimation of costs and benefits is "most difficult because they have not yet occurred" (Cellini & Kee, 2010, p. 497).

A difficulty experienced in constructing the analysis was varying quality and detail of open-source data. Some print processes (e.g., hybrid 3D) were difficult to obtain relatively basic data for (like maximum build weight). Another challenge in comparing the four processes was that some metrics applied to some processes and not others. Two examples of this are the dimensional data of the 3D Hybrid Solutions WAAM machine and the print/deposition rate for the FFF and BDM processes. The inability to establish common metrics across processes, especially relating to build speed, is acknowledged in the AM industry (All3DP, 2022). Inconsistent data across all processes complicated a true parameter vs. cost analysis.

Related to the challenge of finding consistent printer attribute data was the lack of a standardized "test print" from which to easily compare the performance of each metal printer. To establish a total production time for each printer (inclusive of printing and post-processing), ideally each printer would produce the exact same part and the print times would be indicative of the respective performance of each printer (while also revealing print quality characteristics such as accuracy, surface finish, warping, etc.). A standardized 3D print file of a small toy tugboat called "Benchy" has been used since 2015 to calibrate printer and benchmark 3D printing process performance in terms of print time, surface finish, and accuracy (3DBenchy, n.d.). This part is specifically designed to challenge 3D printing machines through complex geometries and other design characteristics, while requiring minimum expenditure of materials and an average print time of approximately two hours in polymer printers (3DBenchy, n.d.). However, this standardized print file is not formally adopted across the industry and may not be the ideal design for benchmarking metal AM processes for military or industrial applications. Thus, without a standardized part, various assumptions were required to be able to determine a representative production time for each printer to allow for comparison and cost-effectiveness analysis. Assumptions are detailed in Section B.

This thesis follows the ten steps of a cost-effectiveness analysis as proposed by Cellini and Kee:

1. Set the framework for the analysis (specify the set of alternative projects)
2. Decide whose costs and benefits should be recognized

3. Identify and categorize costs and benefits
4. Project costs and benefits over the life of the program, if applicable
5. Monetize (place a dollar value on) costs
6. Quantify benefits in terms of units of effectiveness (for CEA), or monetize benefits (for CBA)
7. Discount costs and benefits to obtain present values
8. Compute a cost-effectiveness ratio (for CEA) or a net present value (for CBA)
9. Perform sensitivity analysis
10. Make a recommendation where appropriate (2010, p 495).

Each step is addressed individually in Chapter V, with recommendations addressed in Chapter VI.

B. ASSUMPTIONS

The following assumptions were made to affect the analysis:

- Qualification/Certification: Qualification/certification of printed parts will be resolved (i.e., assume all printed parts are approved for use and all printers are able to meet qualification/certification standards).
- Training: Current USMC machinist MOS (2161) will receive adequate training for expeditionary operation of intermediate-level metal AM.
- Metal and Polymer Employment Model: The USMC will continue to focus on employment of "low-end" polymer printers (e.g., those in TACFAB) by "any Marine/MOS" requiring only minimal formal or on-the-job training.
- Metal and Polymer Employment Model: The USMC will continue to pursue adoption of polymer AM technologies irrespective of metal AM adoption (i.e., polymer integration will continue on a separate path, unaffected by metal AM adoption pathway).
- Polymer material and processes are unable to meet required durability and strength properties of certain repair parts, i.e., metal is a valid requirement and cannot be replicated by existing polymer systems.

- Deployability: Each process will be able to be “containerized,” i.e., small adaptation problems of placing an item in a deployable container can be resolved.
- Operational life: Five-year operational lifetime for all metal AM systems under consideration. Due to the rapid advancement of AM technology, it would be likely that sufficient improvements would be available to justify upgrade to new equipment at the end of five years.
- All XFAB systems will receive identical metal AM equipment suites.
- All metal AM printers will be procured in one purchase transaction, effectively “locking in” the purchase price (i.e., price for printers will not change year-to-year).
- Acquisition of metal AM system will include a five-year service and support contract.
- Acquisition of metal AM system will be a phased process, occurring over a period of four years from 2023 to 2026.
- Test and evaluation costs apply equally to all candidate systems.

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V. COST EFFECTIVENESS ANALYSIS

This chapter details each of the nine steps of the cost effectiveness analysis. Following the method described in Chapter IV, the following elements are discussed: framework for analysis; identification and categorization of costs and benefits; projection of costs over the program lifetime; monetization of costs; quantification of benefits in terms of the chosen unit of effectiveness; calculation of present value of costs; calculation of cost effectiveness ratios; and conduct of a sensitivity analysis.

A. STEP 1: SET THE FRAMEWORK FOR THE ANALYSIS

Step 1 of a CEA establishes the status quo so that the proposed alternatives have a basis of comparison. The status quo is described as “the state of the world in the absence of the program” (Cellini & Kee, 2010, p. 495). Although the USMC does not have a formally adopted program of record metal AM system yet, some operational experience has been accrued with the use of the hybrid AM system in the initial pilot ExMan facility. Therefore, the status quo is considered to be the 3D Hybrid Solutions hybrid AM system, as the Marine Corps has achieved a basic familiarity with the deployment, employment, and capabilities of this system. This status quo facilitates a more focused comparison between the four candidate metal AM systems, rather than a comparison of metal AM against the current system of OEM manufacture and traditional supply requisition process. Additionally, it supports the assumption that existing polymer systems are incapable of producing specific parts with required durability and strength properties, i.e., metal is a valid requirement and cannot be replicated by existing polymer systems. In addition to the existing operational familiarity with hybrid AM, some informal, “hedging” plans exist to adopt a hybrid AM system even if other metal AM systems are also adopted (M. Audette, personal communication, September 30, 2022). These hedge plans are also supported by a hybrid AM status quo, as it acknowledges hybrid AM as an existing system while offering an analysis of complementary systems.

Thus, the hybrid AM status quo is compared against four different courses of action: 1) retain status quo option of hybrid AM; 2) adopt one of the four AM processes and eliminate hybrid AM; 3) retain hybrid AM and add a second, additional process. Primarily due to space constraints within the XFAB facility, the third course of action is eliminated from the analysis. However, if over time demand for metal AM parts rises and a single process is unable to meet all design specifications and requirements, a second process with complementary but distinctly different capabilities may be worth considering. This could entail an additional container for transportation or the elimination of other AM capabilities inside the XFAB to make room for a second metal process. Considering the rate of technological development of metal AM, USMC budget constraints, and that lessons learned from operational experience may produce refined performance requirements, a more conservative approach of comparing the status quo versus the four other processes is used here.

Consideration was given to making "no metal AM capability" the status quo, as the hybrid 3D system has not formally been selected for adoption or acquisition. It is acknowledged that despite the fact that hybrid 3D is currently in use, much more development, acquisition, and integration effort would be required to fully adopt the system. However, these efforts would be required in any of the candidate systems examined and are assumed to apply equally to all systems.

Chapters II and III detailed the operational context and environment in which metal AM systems would be operating. Distributed operations, low signature, and manufacture of "hyper critical" parts at or near the point of need are the key elements to consider moving forward in the analysis.

B. STEP 2: DECIDE WHOSE COSTS AND BENEFITS SHOULD BE RECOGNIZED

In a CEA, determination of "standing," or inclusion as a stakeholder in the cost/benefit analysis, is typically determined by geographical boundaries (e.g., city, county, state, or national). This process is noted to be a major issue for evaluators and heavily influences the results of the analysis (Cellini & Kee, 2010). A narrow scope results in fewer impacts being counted but can also ignore impacts that spill over into adjacent areas, while too broad of an area can result in a muddy analysis and difficulty in determining program effectiveness. Cellini and Kee recommend selecting the jurisdiction or area that will bear most of the costs and experiences the majority of the benefits, while still recognizing and explaining any major spillovers (Cellini & Kee, 2010). For the scope of this research, potential costs and benefits do not extend beyond the internal operations of the USMC. However, a major but diffuse spillover worth acknowledging as a result of this constraint are the costs experienced by the American taxpayer. As the taxpayer is the ultimate bill payer of any AM system adopted by the USMC, they bear an appreciable amount of the cost burden and are ultimately expecting to derive the benefit of national defense and security by funding the Marine Corps. Although the cost is diffused through various budgetary income pathways, the expectation of the American taxpayer (represented by Congress) in bearing the cost is that the Marine Corps will choose the most cost-effective option available.

Considering Cellini and Kee's recommendation to select the entity that experiences most of the costs and benefits, a service-level perspective of the USMC is the appropriate level of analysis for assessing the cost effectiveness of various metal AM systems and impacts to USMC operational effectiveness. Also granted standing in the analysis is the naval/joint force. With the dramatically increased emphasis on naval integration evident in the force design effort, the Marine Corps' support to naval operations should be considered, as naval or joint forces may receive benefits from Marine Corps capabilities. However, these benefits are expected to be small, primarily due to the limited capacity extant in any metal AM system operated by the USMC. At the lowest level of standing is the operational/using unit. These forces stand to benefit the most tangibly through production of critical parts in time of possibly desperate need.

C. STEP 3: IDENTIFY AND CATEGORIZE COSTS AND BENEFITS

The third step in the CEA identifies and categorizes costs and benefits that will have the most impact on system selection. Though not all costs and benefits can be known with certainty, those with the most significant implications on the policy have been attempted to be captured, though not all of these effects require an evaluation in dollars

(Cellini & Kee, 2010). Small or negligible costs and benefits are often ignored or briefly discussed (Cellini & Kee, 2010).

The impacts are divided into the three stakeholders with standing: the naval/joint force, USMC, and using-units. Each perspective contains a cost and benefit category with a description of each impact. While a CEA conducted early in a program should think broadly about costs and benefits, in this thesis the analysis is focused on deployed operation of metal AM printers in expeditionary environments. Thus, costs and benefits are broadly considered, but within the constraints of the operational context.

From the joint/naval force perspective, two costs are identified. If the Marine Corps adopts metal AM capabilities, it is expected that some degree of support will be required from the joint/naval force to support the continued operation of the printer, since the Marine Corps does not operate independently and, at minimum, requires strategic and operational-level lift support from the Air Force and Navy. Often joint operations involve other service's capabilities such as operational contracting; for example, depending on the command and support relationships in theater, the sourcing of raw feedstock for a metal printer could fall on any service's contracting specialists (not just the Marine Corps'). The second cost identified was the opportunity cost to dedicate cubic footage on strategic lift platforms to a metal AM system. This cubic space and weight could be allocated to an infinite number of other resources useful in a theater of operations (e.g., vehicles, food, ammunition). The choice to place a metal AM printer on a platform for movement into theater will inherently mean something else does not make the trip at that given time. Additionally, three benefits were identified. With a metal AM printer in theater, this printer could potentially be tasked to produce parts for any organization in the deployed task force, regardless of service; these joint forces would then share in the benefit of a Marine metal AM capability. Marine forces would also benefit from this capability of course, with the result being an increase in the operational availability of Marine forces in theater (able to conduct missions to provide support to the overall campaign). Lastly, if the Marine forces can produce repair parts locally, this removes some degree of support requirement from the joint/naval force in the form of reduced demand for repair parts. This reduction will be somewhat negated by the creation of demand for raw AM feedstock, but feedstock can create numerous parts while a single, specific part is only good for the one-time, specific application. Table 6 summarizes the impacts for the joint/naval force perspective.

Table 6. Impacts, Joint/Naval Force Perspective

Category	**Description**
Costs	Additional logistical support to Marine forces to enable AM (e.g., feedstock sourcing/supply, vendor-vetting, creation of service contracts)
	Opportunity cost to dedicate cubic footage and weight on L-Class shipping or strategic air lift platforms to USMC AM printers
Benefits	Marine forces can print parts for joint/naval forces if required
	Increased Marine force availability enables increased combat power
	Local production of parts means Marine forces require less intensive/less frequent logistical resupply for repair parts

Impacts at the service-level have increasing amounts of direct costs associated with them, primarily because the service is ultimately the "bill payer" when it comes to acquisition, operation, and maintenance of the AM equipment. The costs at the service level include the initial purchase price of the equipment, which is assumed to the 16 systems (one for each fielded XFAB). Redundant or stand-by systems are not considered in the initial purchase price. Operating costs for five years are considered, conceptually meaning the direct cost of electricity or fuel for generators, feedstock costs, support contracts, etc. Sourcing of raw feedstock is included, both in the direct cost of materials purchase, and in the opportunity or social cost associated with the supply system as a whole adding, tracking, ordering, stocking, inventorying, and issuing a new item in the supply system. The final service-level cost considered is the deployment cost for the AM equipment, as the equipment must be placed in theater to be able to produce benefits.

Benefits at the service level are mostly tangible, operational results directly relating from local production of items on the AM equipment. Local production of metal parts increases Marine force operational availability and available combat power, enabling those forces to contribute to the overall task force objective. Local production of parts also reduces demand for specific repair parts, which may be difficult to obtain in a timely or operationally appropriate manner. This local production also reduced the logistical demand

and signature of Marine forces, as demand has been marginally reduced, requiring fewer or less frequent logistical movements to deliver repair parts. Table 7 summarizes the impacts for the service-level force perspective.

Table 7. Impacts, Service-Level (USMC) Perspective.

Category	**Description**
Costs	Initial purchase price of equipment (16 systems x price)
	Operating costs per year for five years
	Training requirements (more complicated systems require more training)
	Deployment cost (smaller systems cost less to deploy)
	Supply system must now source feedstock for metal AM equipment
Benefits	Local production of parts increases Marine force operational availability and available combat power
	Local production of parts reduces demand for specific repair parts, which may be difficult to obtain
	Local production of parts reduces logistical signature

Impacts at the using unit level reflect the operational employment of the equipment. Before a usable print can be delivered, a process of several steps must occur. The failed part needs to be analyzed for the cause or mechanism of failure so that, if possible, the part design may be improved to prevent the failure from reoccurring. Once the analysis is complete, the operator will design the part to be printed using CAD software and a slicer program, which dissects the part into individual layers to be printed by the machine. The design time cost can be mitigated through the use of a central, digital repository of approved designs, as envisioned by the Marine Corps AMOC. After the machine is prepared for operation, the actual print can begin. Print time will vary greatly depending on the generic print process employed, specific printer model build rate, the geometric complexity of the part design, and the material used for the part. Once printing is complete, the part will move to post-processing. Not all parts will require post-processing; post-processing requirement are influenced by the print process employed, part material, and desired final part properties (i.e., surface finish or dimensional tolerances). All of these steps come at a cost to the using unit. However, the part production costs (in terms of time) described are inherent in the operator’s MOS as a machinist, so the costs fall largely within the pre-existing opportunity cost of employing a Marine as a machinist, performing machinist duties, rather than in another position or skill set.

Additionally, the preventative and corrective maintenance actions required through continued operation of the machinery incur a cost on the using unit. Some of these actions may be covered under warranty or service contract from the AM OEM provider, but others such as routine preventative maintenance, fall on the operator to conduct. The unit-level supply section also has a requirement to stock and supply the AM machinery with feedstock and maintenance items; this could be handled through a variety of mechanisms depending on circumstances (i.e., deployed or in garrison), but the cost remains the same in terms of supply providing access to new or additional items. The final cost identified is the potential for an increased physical footprint or detectable signature from the presence of AM equipment in theater. As the metal AM systems are planned to only be employed inside of the XFAB (and likely only in conjunction with the SEMS), the tactical decision to employ metal AM will entail bringing the entire XFAB and SEMS to theater. These systems incur an added physical footprint and signature as added logistical support elements to the primary combat force, bringing an increased potential of detection, targeting, and attack.

Benefits at the using unit level are seemingly small in quantity, but the impact of the two identified benefits is significant. Decreased MDT through rapid part accessibility leading to increased operational availability of combat-essential equipment can directly impact the execution and outcome of tactical operations. Additionally, the presence of metal AM equipment, combined with the individual Marine's ingenuity and design skill, can produce novel solutions to material challenges on the battlefield. These two benefits drive at the essence of the desired outcome of the expeditionary metal AM program. Table 8 summarizes the impacts for the using-unit level perspective.

Table 8. Impacts, Using Unit (Deployed) Perspective

Category	Description
Costs	Design time for each unique part
	Print time for each individual part
	Post-processing time for each individual part
	Maintenance time dedicated to metal AM equipment
	New requirement for supply of feedstock for metal AM equipment
	Increased physical footprint from additional equipment (system dependent, as not all systems increase footprint)
Benefits	Decreased MDT (via decreased ADT and LDT) resulting in increased operational availability for unit equipment
	Ability to harness individual ingenuity to produce unique parts to remedy emergent equipment deficiencies or part failures

D. STEP 4: PROJECT COSTS AND BENEFITS OVER THE LIFE OF THE PROGRAM, IF APPLICABLE

This section of the CEA establishes the time frame for the analysis, over which changes in costs and benefits can be observed. CEAs may be conducted over any length of time, with most analyses considering a period ranging from five to fifty years depending on the project (Cellini & Kee, 2010). Cellini and Key recommend focusing on the *useful life* of the program that is sufficient to capture most costs and benefits (Cellini & Kee, 2010).

While the XFAB facility may operate for many decades, AM technology is seeing tremendous developmental gains in relatively short amounts of time. Thus, the XFAB offers the modularity that allows for AM equipment to be updated when newer technology offers a significant enough benefit to justify the cost spend to upgrade the equipment. Roach notes in his discussion of the XFAB that “system updates, modifications, and improvements will be applied as part of the life-cycle support plan” and that the “modular design allows for printer upgrades, engineering changes, and planned technology refreshes to mitigate technology obsolescence” (Roach, 2021, para. 14). Thus, the AM and support equipment inside the XFAB will likely be replaced at a rate that is commensurate with the rate of technology improvement, balanced with the opportunity cost of an update. Conversely, despite the lure of the newest technology, it would be uneconomical, in terms of both simple acquisition cost and time to train equipment operators, to replace equipment at very short intervals (i.e., annually). Therefore, a shorter time frame is felt to be more appropriate for this analysis.

A time frame of five years was selected, as this is believed to offer a reasonable, conservative "middle ground" that offers the benefits of recent technological capabilities, while allowing the Marine Corps to develop refined training processes and build operator proficiency with a suite of AM equipment. A market research study done in 2021 by manufacturing consulting firm Jabil found that "ninety-seven percent of manufacturers polled expect their use of 3D printing to grow within the next five years" and that industry's growing acceptance of AM will be driven in part by the accessibility of the technology (Jabil, 2021, p. 11). During this five-year period, industry will continue to advance AM technologies while the Marine Corps can gain experience employing AM in operational environments. A relatively stable (i.e., unchanging) equipment set allows for increased benefits through operator proficiency and increased institutional familiarity with the capabilities and application of AM technology. As individual and institutional proficiency is established, the introduction of new, state-of-the-art equipment will offer increased benefits. The primary driver in changes in costs and benefits are the advancements in organizational attitude towards adoption and integration of metal AM into maintenance activities. As the organization is exposed to the capabilities of metal AM, and processes and procedures are adopted to reflect the integration of the technology, it is expected that metal AM will see increased usage. This increased usage is the source of many changes in costs and benefits over the five-year period.

Although not a change in cost, the most significant cost is the initial up-front investment to acquire the chosen system which, once the systems are purchased, will not change over the five-year period. This requires the assumption that the metal AM equipment will be purchased in a batch or lot, with all printers being purchased for the same nominal price in constant dollars (i.e., equipment prices will not rise year-to-year, making the last printer suite nominally more expensive than the first). As indicated by Roach, the Marine Corps intends to field 16 XFAB systems by 2026, with each system presumably having identical equipment sets (2021, para. 14). This then means any equipment procurement will be fully fielded across the 16 systems.

Three changes in costs across the five-year period were identified. A better institutional and individual understanding of the capabilities of metal AM (and AM in general) is expected to bring about increased AM system usage as more production requests are demanded of the systems. Additionally, as the metal AM systems are more regularly relied upon, this will bring about more frequent deployment and employment in expeditionary environments. Through increased demand for the capability, AM equipment will be exposed to transportation risks and harsh environmental conditions in austere locations. This increased usage is expected to bring about a requirement for more frequent preventative and corrective maintenance. Increased preventative maintenance results from routine wear-and-tear on the machinery, while an increase in corrective maintenance is expected as the machinery experiences unexpected or emergent failures due to employment and environmental stresses.

Another expected change in costs is the price of the feedstock and raw materials required for printing. As the collective group of feasible printers are capable of printing in a wide variety of metals, prices for these AM-ready feedstocks can vary over time and by material. Feedstock and raw material prices can increase over time due to both inflationary effects and market effects as demand across industry increases. Price increase due to increased demand could potentially be offset by increased supply as market opportunities expand for suppliers.

A potential, less tangible cost over the five-year period is the opportunity cost experienced by not being able to upgrade to newer equipment as the capability of metal AM technology progresses. With the assumption that a “tech refresh” will not occur within the five-year period, there is the potential that significant metal AM technology advancements may not be able to be adopted, leaving the Marine Corps with outdated, less-capable technology. Such is the rate of advancement in the AM industry that equipment can be considered “outdated” after five years. However, this cost is considered low, as the institutional rate of adoption of metal AM is slow enough that any systems owned will likely still be relevant and perform within Marine Corps expectations. After the five-year period, updating metal AM equipment to the current industry-standard will likely produce greater results, as the organizational adoption and integration of AM will have "caught up" to the capabilities of the technology.

A change in cost not considered in this analysis is costs associated with the training of metal AM equipment operators. This change in cost is not considered as AM training is already incorporated into the current 2161 machinist occupational specialty school, and therefore no additional, unique formal-school training is required (HQMC, 2018). Updates to training materials and curriculums may be required, but these are not considered as school faculty inherently conduct periodic updates to all curricula and any costs are considered a transfer. On-the-job training may be required to train operators on specific equipment procedures based on frequent part demands or unit standard operating procedures, but as this type of training is inherent in both the MOS community and all Marine units it is not considered in this analysis.

Four changes in benefits over the five-year period of analysis were identified, with most benefits being realized as a result of increased usage of metal AM capabilities. As metal AM increases in adoption and integration, it is expected that increasing amounts of unique parts will be requested for local manufacture on IMA metal AM equipment. For the first time a unique part is desired to be produced via AM, a design, test-fit/prototyping, and approval process will be required, as illustrated in Figure 16. As each part is designed by machinists and approved by the Marine Corps' AMOC, these parts will be catalogued for future use (HQMC, *MCO 4700.4,* 2020). This cataloging of approved and certified parts will reduce the individual part production time, as the design and prototyping steps will be eliminated. With a requested part able to jump immediately to the production queue, reductions in mean downtime (MDT) are expected as a result of reduced administrative downtime (ADT).

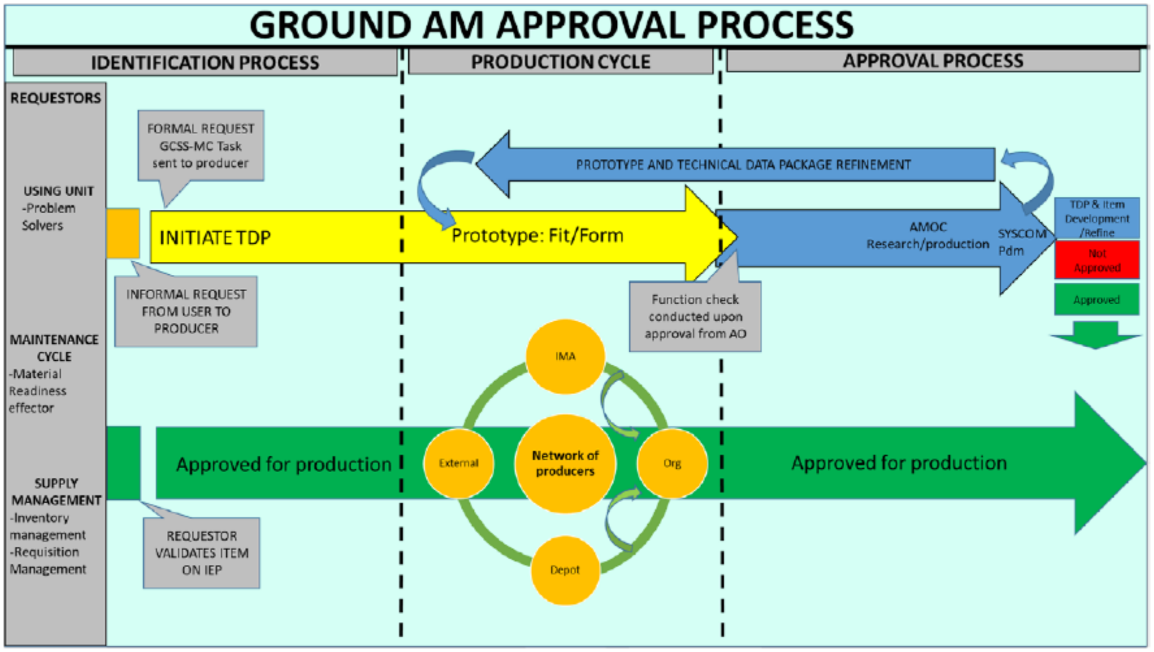


Figure 16. Ground AM Approval Process As Illustrated in *MCO 4700.4*. Source: HQMC (2020).

Throughout the five-year period, it is expected that operator proficiency with the metal AM systems will improve (especially if the systems remain constant, as discussed previously). As proficiency increases, a reduction in part production times is expected. This reduction is realized through increased operator experience in part design, computer-aided design skills, machine operation, prototyping, and familiarity with the certification/ approval process. Another expected change in benefit generated from higher operator proficiency is increased prevalence of novel applications of metal AM technology. As operators gain a better understanding of the capabilities and limitations of the systems, it is likely that new uses for AM-produced metal parts will be conceived, producing "homegrown solutions" to operational problems resulting from ineffective OEM design or materials.

The final projected change in benefit is an improvement to the metal printer technology found in the XFAB. As Marine units deploy and operate with the XFAB and associated metal printers, a significant amount of technical and operational knowledge will be generated. These lessons learned should be relayed to the equipment manufacturers so that their products can be improved. While some improvements may be significant enough to warrant an entire system upgrade, others may be incremental and evolutionary and able to be applied to the AM equipment within the five-year period. When combined with increased operator proficiency, equipment improvements have the potential to function as an additional multiplier to increase part production capacity and capability. Table 9 summarizes the projected changes in costs and benefits over the five-year analysis period.

Table 9. Summary of Projected Changes in Costs and Benefits

Impact	**Projected Changes over Five-Year Period**
Costs	Increased preventative and corrective maintenance required due to increased system use and expeditionary environment conditions
	Increased cost of feedstock(s) due to inflation or market effects
	Dramatic improvements in technology unable to be incorporated into XFAB
Benefits	Reduced MDT on ground equipment as more parts are catalogued and approved for local AM production
	Faster part production times due to increased operator proficiency
	Novel applications for metal AM discovered through increased operator proficiency (i.e., “homegrown solutions”)
	Improvements in printer technology resulting from feedback from operational forces

E. STEP 5: MONETIZE COSTS

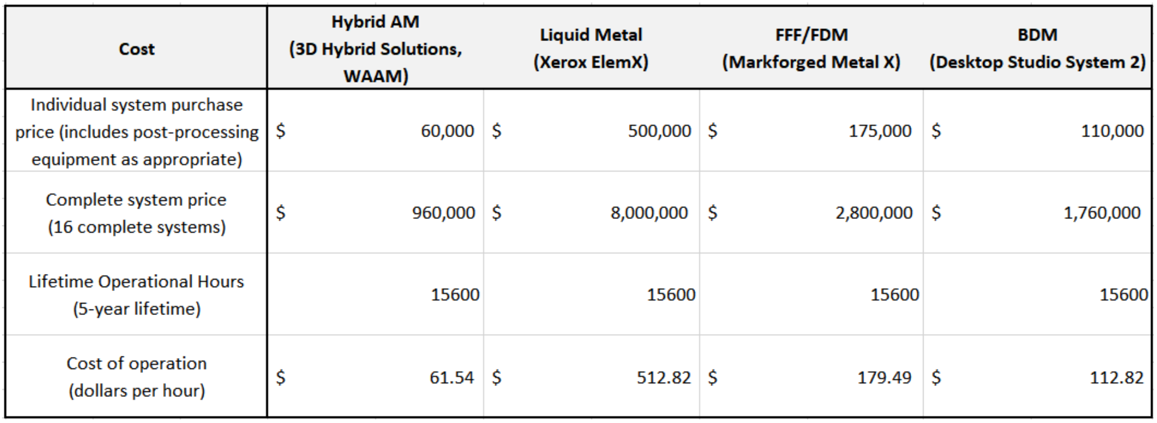
Although difficult (or impossible in some instances), monetization of costs provides a familiar metric to facilitate comparison between options and should include a description and measurement of the cost along with any relevant assumptions (Cellini & Kee, 2010). In this analysis, monetization of costs focuses on direct costs associated with printer acquisition and operation. Not all identified impacts require an evaluation in dollars (Cellini & Kee, 2010). Monetization of metal AM machines is difficult, as the candidate technologies are still so new that little reliable cost data exists, and each machine/process has inherent costs unique to the process (e.g., proprietary feedstock rods for FFF and BDM processes). Benedict O’Neill from AM consulting firm Aniwaa notes that, “many of these metal 3D printing costs are hard to quantify accurately in advance; others are so hidden they might be forgotten about entirely” (O’Neill, 2021, para. 2). O’Neill’s description of total cost of metal AM ownership consists of initial investment costs and operating costs are shown in Table 10.

Table 10. Generic Metal AM Ownership Costs. Source: O’Neill (2021)

Initial Investment Costs	**Operating Costs**
Metal 3D printer	3D printer maintenance
Supplementary machines (post-processing, powder management, sintering furnace, etc.)	Consumables (printing powders/filaments, compressed gas, post-processing, etc.)
Facility equipment (air conditioning, fire safety, etc.)	Software (subscription)
Software (perpetual license)	Staff salaries
Training and installation	Rent and other utilities

The costs identified in Step 3 were narrowed down to only those with the most significant implications on printer selection. Costs were monetized for each printer/process using open-source cost data, sourced from a combination of manufacturer and industry-consultant websites. The quoted price of $50,000 per print head for the 3D Hybrid Solutions system was from 2018; this price was adjusted for inflation to 2022 dollars using the U.S. Bureau of Labor Statistics CPI Inflation Calculator, resulting in a per-print-head price of $59,940.93 (rounded to $60,000) (U.S. Bureau of Labor Statistics, n.d.). This data while potentially biased, is considered to be adequate for the development of an initial decision-making framework. Specific quotes from manufacturers based on contractual bases would be required to conduct a definitive assessment of the true costs of metal AM printer acquisition. Table 11 shows the refined list of costs to be evaluated in dollars and monetization of these costs.

Table 11. Monetization of Selected Costs



Cost	Hybrid AM (3D Hybrid Solutions, WAAM)	Liquid Metal (Xerox ElemX)	FFF/FDM (Markforged Metal X)	BDM (Desktop Studio System 2)
Individual system purchase price (includes post-processing equipment as appropriate)	$ 60,000	$ 500,000	$ 175,000	$ 110,000
Complete system price (16 complete systems)	$ 960,000	$ 8,000,000	$ 2,800,000	$ 1,760,000
Lifetime Operational Hours (5-year lifetime)	15600	15600	15600	15600
Cost of operation (dollars per hour)	$ 61.54	$ 512.82	$ 179.49	$ 112.82

Individual system prices were gathered from the following sources: Hybrid 3D: Jackson (2018); ElemX: Basiliere (n.d.); FFF: Markforged (n.d.); BDM: Kauppila (2022).

For calculation of "cost of operation," a format for determining 3D printing cost from prototyping and rapid manufacturing company Wayken was used. The methodology first determined the total operating hours over the projected lifespan of the printer. Daily operation was assumed to be 12 hours per day over a 5-day week, with 52 weeks in a year multiplied by the 5-year analysis period:

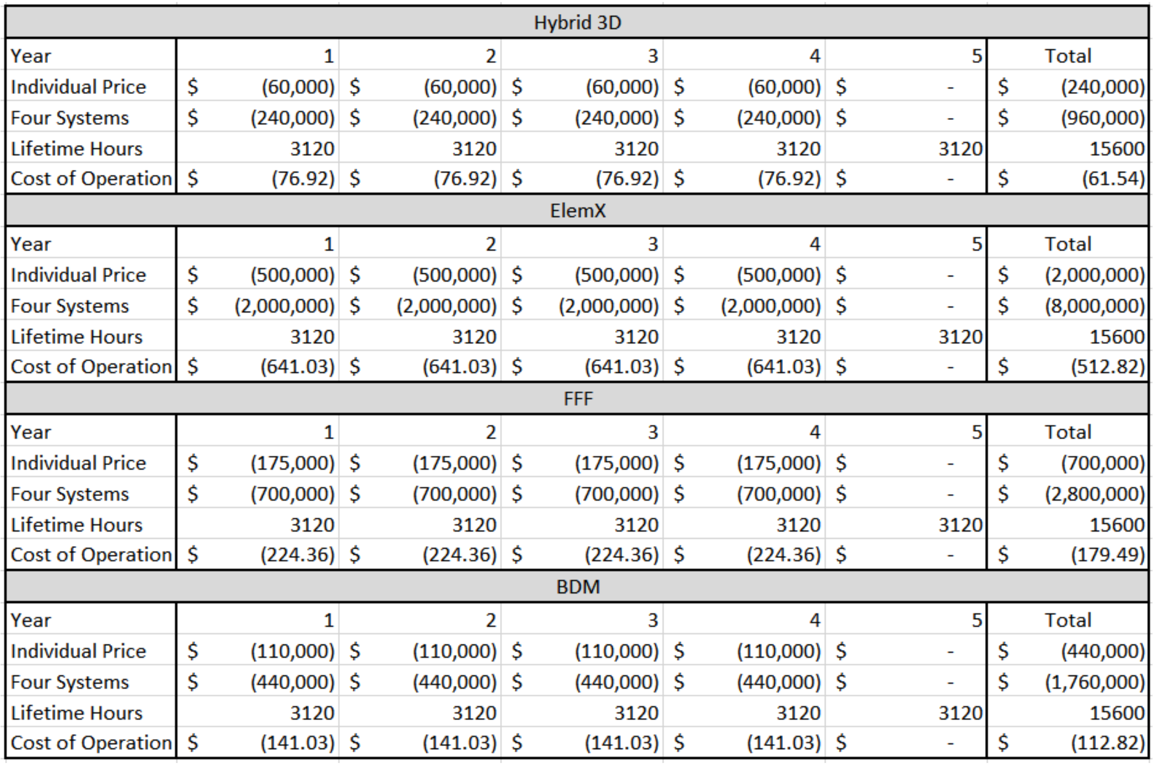
$$12\ hours\ per\ day \times 5\ days\ per\ week \times 52\ weeks\ per\ year \times 5\ years = 15600\ hours\ per\ year$$

The total purchase price of each printer was then divided by the lifetime operational hour total, giving the lifetime cost of operation in dollars per hour for each printer. These calculations offer an initial analysis of the costs associated with each candidate printer.

A significant assumption for the above calculations is that all 16 systems are purchased in a single action occurring in a single year, and that all systems are fielded and operational in that year. For a relatively modest cost like this purchase represents, this is reasonable. However, according to Roach, the Marine Corps intends to have 16 XFAB facilities fielded by 2026, indicating a phased adoption of the systems. This phased adoption, assumed to begin in 2023, would see four systems purchased each year for four years until 2026, when 16 complete XFABs will be fielded. The Marine Corps AMOC indicates the XFAB will undergo a "tech refresh" and receive a metal AM capability in

2025 (M. Audette, personal communication, September 30, 2022). Using the XFAB phased adoption as precedent, it is assumed that the metal capability will also be phased. The phased introduction of metal AM systems into the XFAB allows for iterative and recursive system improvements, as integration problems experienced in earlier years will enable smoother integration in later years. While all 16 systems could be acquired and fielded simultaneously, the phased approach offers system integration benefits and is therefore carried forward in the analysis as an assumption. The phased adoption plan is shown in Table 12.

Table 12. Monetization of Costs, Phased Adoption



Hybrid 3D						
Year	1	2	3	4	5	Total
Individual Price	$ (60,000)	$ (60,000)	$ (60,000)	$ (60,000)	$ -	$ (240,000)
Four Systems	$ (240,000)	$ (240,000)	$ (240,000)	$ (240,000)	$ -	$ (960,000)
Lifetime Hours	3120	3120	3120	3120	3120	15600
Cost of Operation	$ (76.92)	$ (76.92)	$ (76.92)	$ (76.92)	$ -	$ (61.54)
ElemX						
Year	1	2	3	4	5	Total
Individual Price	$ (500,000)	$ (500,000)	$ (500,000)	$ (500,000)	$ -	$ (2,000,000)
Four Systems	$ (2,000,000)	$ (2,000,000)	$ (2,000,000)	$ (2,000,000)	$ -	$ (8,000,000)
Lifetime Hours	3120	3120	3120	3120	3120	15600
Cost of Operation	$ (641.03)	$ (641.03)	$ (641.03)	$ (641.03)	$ -	$ (512.82)
FFF						
Year	1	2	3	4	5	Total
Individual Price	$ (175,000)	$ (175,000)	$ (175,000)	$ (175,000)	$ -	$ (700,000)
Four Systems	$ (700,000)	$ (700,000)	$ (700,000)	$ (700,000)	$ -	$ (2,800,000)
Lifetime Hours	3120	3120	3120	3120	3120	15600
Cost of Operation	$ (224.36)	$ (224.36)	$ (224.36)	$ (224.36)	$ -	$ (179.49)
BDM						
Year	1	2	3	4	5	Total
Individual Price	$ (110,000)	$ (110,000)	$ (110,000)	$ (110,000)	$ -	$ (440,000)
Four Systems	$ (440,000)	$ (440,000)	$ (440,000)	$ (440,000)	$ -	$ (1,760,000)
Lifetime Hours	3120	3120	3120	3120	3120	15600
Cost of Operation	$ (141.03)	$ (141.03)	$ (141.03)	$ (141.03)	$ -	$ (112.82)

The total purchase price and cost of operation in Table 15 match the simpler model in Table 14. However, the costs do not factor in the progression of time and the time-value of money; this issue is addressed in Step 7.

Maintenance and service costs were assumed to be zero over the five-year period of this analysis, as it is assumed that acquisition of a metal AM system would include warranty and service additions to the contract. Cases when the printers experience a failure in a deployed or expeditionary environment would be handled by uniformed personnel. However, the frequency of failures in these conditions where using units would be entirely without contract support over the five-year period are considered minimal and therefore their effect on the cost analysis is considered negligible.

Material cost was considered but ultimately not included in the analysis. While certain applications may require higher quality materials with better strength properties (e.g., titanium), the amount in which these materials are a true requirement is unknown. Additionally, the amount of cases in which an exotic material such as titanium is required are considered to be minimal and would have a negligible effect on the cost analysis. An additional complication to material cost calculations is the varying amounts of material required per part. For example, a part requiring 3kg of aluminum could potentially cost more than a part requiring 10g of titanium. The average total material required per part is unknown and is subject to waste factor from print or operator errors (which can be driven by the complexity of both the part design and the operation of the printer itself). Ignoring raw material inventory ultimately allows for a better focus on the main trade-offs between printer processes and is an assumption consistent with the literature (Song & Zhang, 2020).

Other costs identified in Step 3 were not monetized as they were considered equal among alternatives:

- Additional logistical support to Marine forces to enable AM operations (e.g., feedstock sourcing/supply, vendor-vetting, creation of service contracts)
- Opportunity cost to dedicate cubic footage on L-Class shipping to USMC AM printers
- Deployment cost (smaller systems cost less to deploy)
- Supply system must now source feedstock to supply using units metal AM equipment

- Maintenance time dedicated to metal AM equipment
- Opportunity costs to train Marines on equipment
- Increased physical footprint from additional equipment
- New requirement for using unit to supply feedstock for metal AM equipment
- Design time for each unique part
- Training required for each system (more complicated systems require more training)

F. STEP 6: QUANTIFY BENEFITS IN TERMS OF UNITS OF EFFECTIVENESS (FOR CEA)

Unlike a CBA that attempts to monetize all benefits, a CEA acknowledges the difficulty in monetizing certain benefits and instead quantifies only the most significant benefit to get a measure of units of effectiveness (Cellini & Kee, 2010). The difficulty in valuation makes the CEA more appropriate than the CBA, but the task is not necessarily any easier. In a book on cost-benefit analysis for military contexts, the authors note that,

> Government decisions in general, and defense resource allocation decisions in particular, have an added evaluation challenge. Outcomes are difficult, if not impossible, to represent in monetary terms. First, benefit cannot be expressed in terms of profit… Second, market mechanisms often do not exist for "pricing out" the many benefits derived from public sector decisions. (Wall & MacKenzie, 2015, p. 198)

As discussed in Chapter II, the perceived anecdotal benefits of metal AM are often cited to be hyper-local production of critical, combat-essential parts to reduce logistics delay time and allow inoperable equipment to be returned to action as quickly as possible. While "saving time" is a goal in this context, the outcome ultimately most useful in military contexts is the continued, reliable operation of critical pieces of equipment (with minimization of maintenance downtime being a contributing factor). The relevance of timely return of equipment to operational status was encountered by 3D printer manufacturer Cosine, who noted a Marine's comment on the utility of Cosine's AM1 printer on a NATO exercise in Norway: “The AM1 has greatly improved our flexibility in the battlefield, allowing us to have a quick turnaround of parts to keep vehicles and units operational on the roughest environments” (Cosine Additive, 2019, para. 9). This operational result is the outcome desired for expeditionary AM. However, complicating the assessment of operational benefits are the actions occurring before the print process and after the final part is produced: the supply system must supply raw print material, while maintainer personnel must install the AM produced parts. The AM process itself cannot control these two steps, so intuitive program outcomes in terms of the operational availability or readiness of deployed force are problematic for assessing a metal AM process’s cost effectiveness.

Thus, the best surrogate for translating results to the battlefield is the number of parts produced by a printer. The quantity of parts produced is influenced by several factors, including a printer’s total production time (printing and post-processing) and the actual demand levels from operational units. It is acknowledged that simple quantity of parts produced does not equate to battlefield success; the produced parts must first be fitted to inoperative equipment by maintainers, and those parts must be fitted to equipment of military significance rather than low-priority, ancillary pieces. This limitation is mitigated by the assumption that a part production prioritization process will be in place for AM expeditionary operations, ensuring that the parts associated with the most critical pieces of equipment are prioritized over all other criteria.

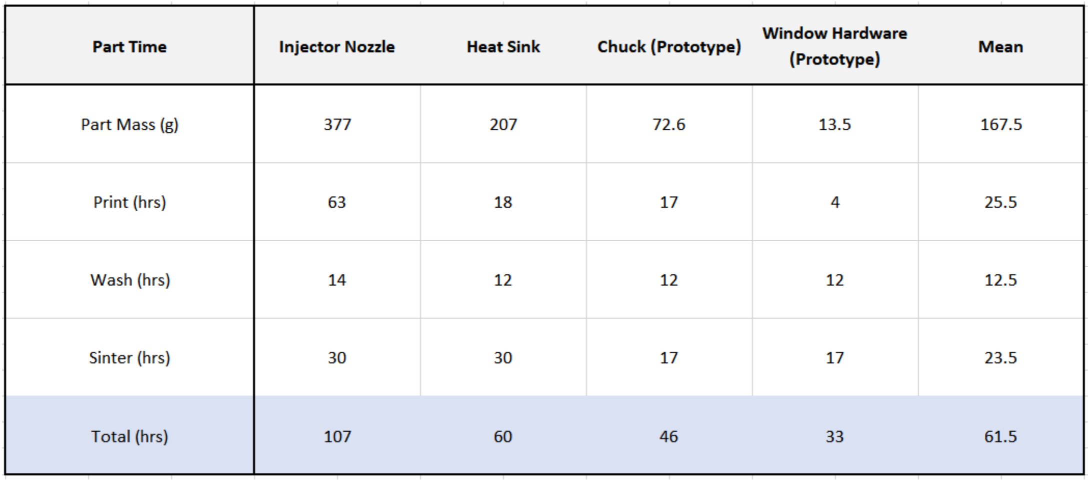
To determine the quantity of parts produced, production times for each process need to be established. Total production time (or simply production time) includes print time plus post-processing time. Differing production times were selected for each process to reflect the inherent differences in actual print speed and post-processing time requirements. Without a standardized part with which to compare print times, the following methodology was used to establish a representative print time and production time.

To account for the wide range in production times that depend on specific part attributes and part geometries, the representative status quo production time was established at nine hours (six hours print time plus 50% for milling). The wire-arc DED technology employed in the 3D Hybrid Solutions system was described as having a faster print rate than most other AM processes (RAMLAB, n.d.). However, this process still requires machining to produce a final part, resulting in the second-fastest production time behind liquid metal.

As the ElemX liquid metal printer has a fast production time (Magnussen, 2022) and it does not have a requirement for post-processing, the production time was established at six hours. This six-hour production time was based on the maximum deposition rate of 0.5 lbs./hour and a maximum part weight of 2 lbs. (producing a theoretical fastest print time of a max-weight part of four hours), plus 50% to account for geometric complexities that will slow the print rate below the theoretical maximum.

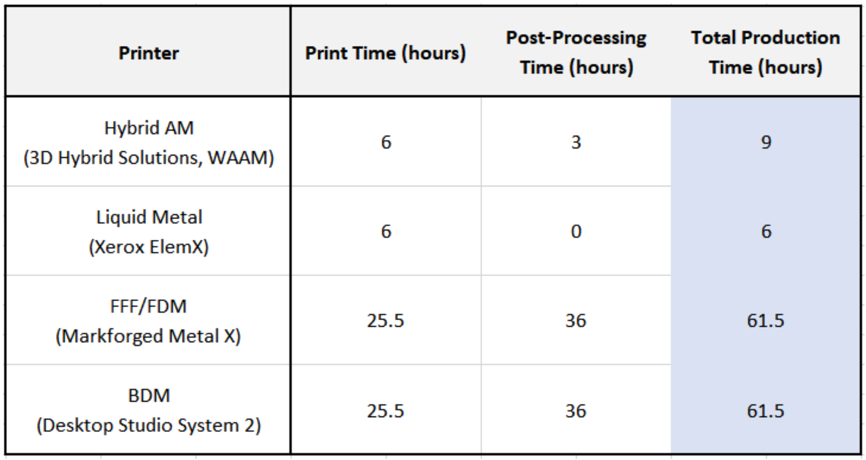
FFF and BDM were given equal times despite BDM's lack of debinding wash, as the lack of wash typically necessitates a longer sintering time for binder removal (Markforged, n.d.). Print times for both systems were determined using metal FFF cycle time data available from Markforged (n.d.b.). The data provided included part mass (grams), print time (hours), wash time (hours), and sintering time (hours). Using the available data, a mean production time of 61.5 hours was found. A summary of the FFF production data (also being applied to BDM) is shown in Table 13. A summary of all four representative production times is shown in Table 14.

Table 13. Summary of FFF Production Times. Adapted from Markforged (n.d.b.)



Part Time	Injector Nozzle	Heat Sink	Chuck (Prototype)	Window Hardware (Prototype)	Mean
Part Mass (g)	377	207	72.6	13.5	167.5
Print (hrs)	63	18	17	4	25.5
Wash (hrs)	14	12	12	12	12.5
Sinter (hrs)	30	30	17	17	23.5
Total (hrs)	107	60	46	33	61.5

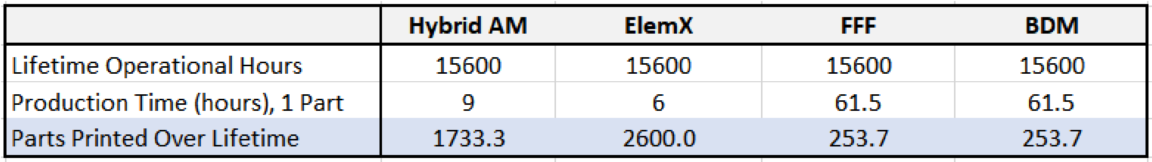
Table 14. Summary of Representative Print Times for Each Process.



Printer	Print Time (hours)	Post-Processing Time (hours)	Total Production Time (hours)
Hybrid AM (3D Hybrid Solutions, WAAM)	6	3	9
Liquid Metal (Xerox ElemX)	6	0	6
FFF/FDM (Markforged Metal X)	25.5	36	61.5
BDM (Desktop Studio System 2)	25.5	36	61.5

With production times for each printer determined, quantification of benefits is possible (in terms of the number of parts produced over the system lifetime). By dividing lifetime operational hours by a representative production time for one part, the number of parts printed over a given system's lifetime can be determined. Table 15 indicates the total number of lifetime parts for each printer.

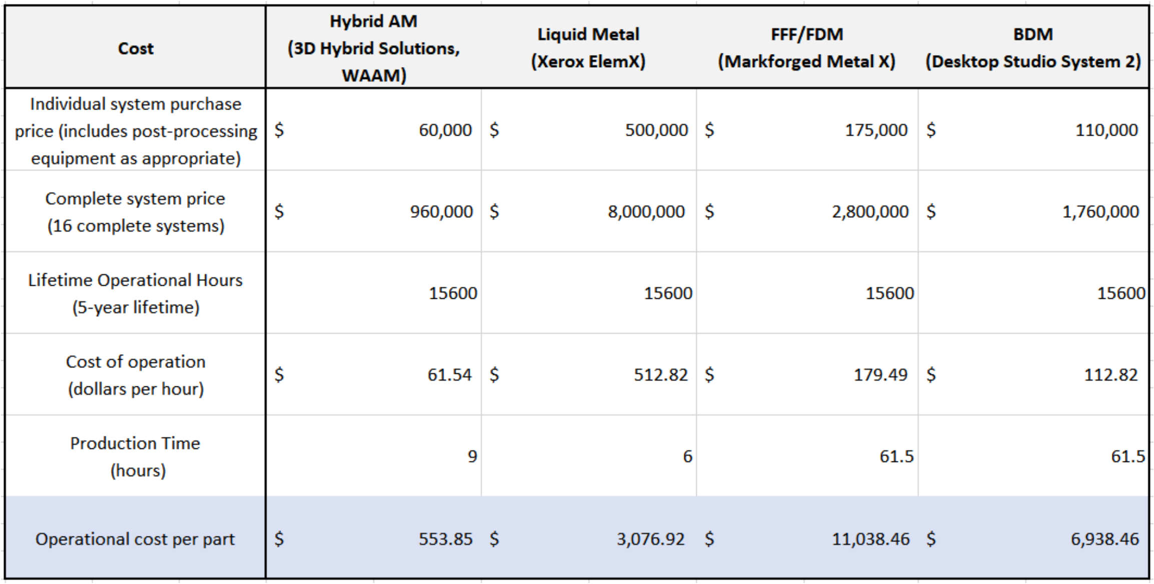
Table 15. Total Number of Parts Produced, by Printer.



	Hybrid AM	ElemX	FFF	BDM
Lifetime Operational Hours	15600	15600	15600	15600
Production Time (hours), 1 Part	9	6	61.5	61.5
Parts Printed Over Lifetime	1733.3	2600.0	253.7	253.7

If the quantity of parts produced is the proxy measure for the desired outcome, then the cost per part becomes an additional perspective on the quantification of benefits and possible decision metric. To determine the cost per part produced, the cost of operation value found in Step 5 was multiplied by a representative production time for each printer technology. The operational cost per part for each printer is shown in Table 16.

Table 16. Quantification of Benefits Added into Monetization of Benefits.



Cost	Hybrid AM (3D Hybrid Solutions, WAAM)	Liquid Metal (Xerox ElemX)	FFF/FDM (Markforged Metal X)	BDM (Desktop Studio System 2)
Individual system purchase price (includes post-processing equipment as appropriate)	$ 60,000	$ 500,000	$ 175,000	$ 110,000
Complete system price (16 complete systems)	$ 960,000	$ 8,000,000	$ 2,800,000	$ 1,760,000
Lifetime Operational Hours (5-year lifetime)	15600	15600	15600	15600
Cost of operation (dollars per hour)	$ 61.54	$ 512.82	$ 179.49	$ 112.82
Production Time (hours)	9	6	61.5	61.5
Operational cost per part	$ 553.85	$ 3,076.92	$ 11,038.46	$ 6,938.46

Operational cost per part is new data; all other data is reproduced from Table 11. Individual system prices were gathered from the following sources: Hybrid 3D: Jackson (2018); ElemX: Basiliere (n.d.); FFF: Markforged (n.d.); BDM: Kauppila (2022).

Given that the lifetime operational hours are constant for all systems, the lifetime production output for each printer is solely influenced by the production time for a single part. With the fastest production time overall, the ElemX shows a clear advantage over the other systems in terms of total parts produced over a five-year lifetime. However, the print times used here are not based on a specific part but rather are representative times based on general system attributes like process, material, and post-processing requirements, so true production numbers can vary widely depending on the specific parts produced.

G. STEP 7: DISCOUNT COSTS AND BENEFITS TO OBTAIN PRESENT VALUES

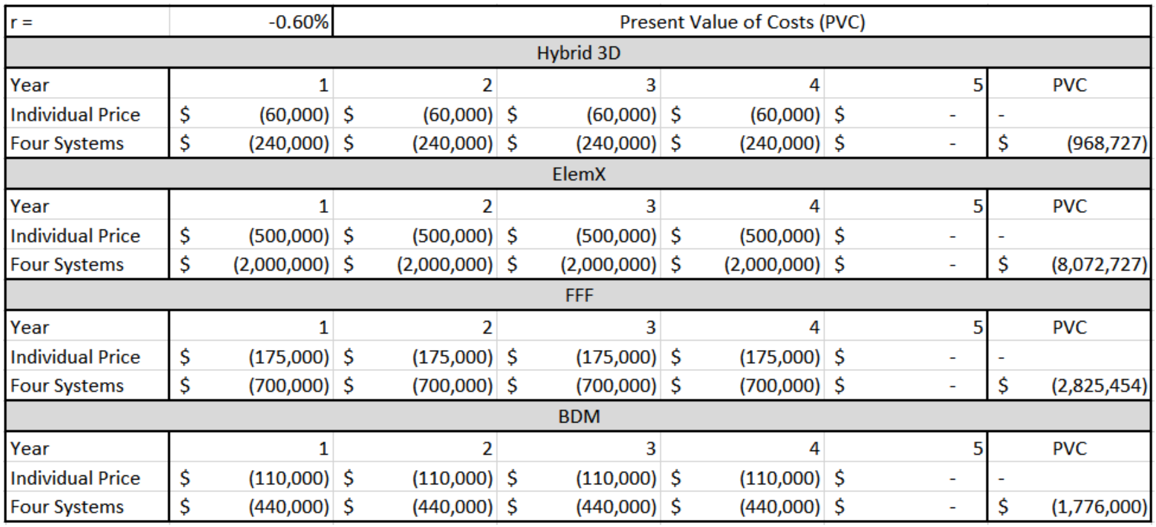
A fundamental principle in CBA or CEAs is the time-value of money, meaning that, even when ignoring inflation, a dollar today is worth more than a dollar tomorrow. This valuation stems from the opportunity cost of money, meaning that a dollar received today could be invested to earn more money in the future, with the exact future amount dependent on the interest rate available. For CBA and CEA applications, a discount rate is used rather than a traditional financial interest rate. The discount rate is meant to “reflect society’s impatience or preference for consumption today over consumption in the future” (Cellini & Kee, 2010). To reflect this concept in a CEA, all monetary values are converted to their present value, i.e., the equivalent value at the beginning of the program Cellini & Kee, 2010).

The formula used to calculate the PVC aggregates the costs in each year (C_t), and converts them to the year 1 equivalent, where r is the discount rate, t is the year:

$$PVC = C_1 + \frac{C_2}{(1+r)^1} + \frac{C_3}{(1+r)^2} + \frac{C_4}{(1+r)^3} + \frac{C_5}{(1+r)^4} + \ldots \frac{C_r}{(1+r)^{r-1}} = \sum_{t-1}^{T} \frac{C_r}{(1+r)^{t-1}}$$

A PVC was calculated for each candidate printer, as each represents a different program option and outcome. A discount rate of -0.6% was used per the March 2022 OMB Circular A-94. The results of the PVC calculations are shown in Table 17. This PVC will be used to determine the cost-effectiveness ratio for each alternative program in Step 8.

Table 17. Present Value of Costs



r =	-0.60%	Present Value of Costs (PVC)				
Hybrid 3D						
Year	1	2	3	4	5	PVC
Individual Price	$ (60,000)	$ (60,000)	$ (60,000)	$ (60,000)	$ -	-
Four Systems	$ (240,000)	$ (240,000)	$ (240,000)	$ (240,000)	$ -	$ (968,727)
ElemX						
Year	1	2	3	4	5	PVC
Individual Price	$ (500,000)	$ (500,000)	$ (500,000)	$ (500,000)	$ -	-
Four Systems	$ (2,000,000)	$ (2,000,000)	$ (2,000,000)	$ (2,000,000)	$ -	$ (8,072,727)
FFF						
Year	1	2	3	4	5	PVC
Individual Price	$ (175,000)	$ (175,000)	$ (175,000)	$ (175,000)	$ -	-
Four Systems	$ (700,000)	$ (700,000)	$ (700,000)	$ (700,000)	$ -	$ (2,825,454)
BDM						
Year	1	2	3	4	5	PVC
Individual Price	$ (110,000)	$ (110,000)	$ (110,000)	$ (110,000)	$ -	-
Four Systems	$ (440,000)	$ (440,000)	$ (440,000)	$ (440,000)	$ -	$ (1,776,000)

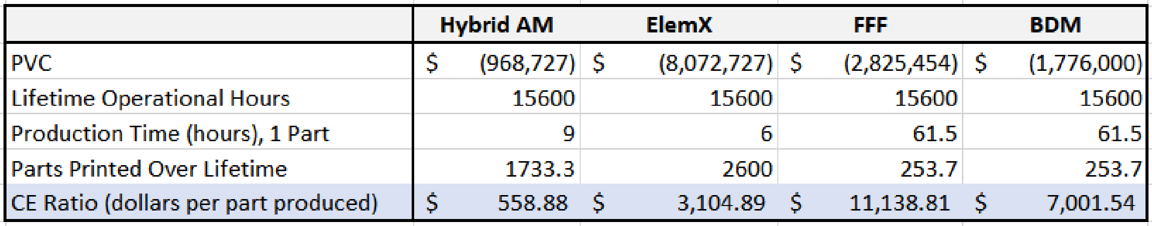
H. STEP 8: COMPUTE A COST-EFFECTIVENESS RATIO

With PVC and units of effectiveness determined, the two metrics can be used to calculate a CE ratio, which is a single measure of program effectiveness (Cellini & Kee, 2010). As explained by Cellini and Kee (2010), the cost effectiveness-ratio is determined by:

$$Cost - Effectiveness\ Ratio = \frac{PVC}{Units\ of\ Effectivness}$$

The result is expressed in “dollars per part printed.” Cellini and Kee offer a caution that CE ratios can obscure differences in scale, potentially resulting in CE ratios between projects with very different costs and benefits appearing approximately equal (Cellini & Kee, 2010). Considering this caution, it is important to emphasize the different in PVC between the four programs; however, the production time for each printer mitigates a significant amount of the influence of cost on the CE ratio (e.g., the high cost of ElemX mitigated by faster production time). Table 18 shows a summary of the CE ratio for each printer. Figure 17 depicts the CE ratios graphically.

Table 18. Cost Effectiveness Ratios for Each Printing Process



	Hybrid AM	**ElemX**	**FFF**	**BDM**
PVC	$ (968,727)	$ (8,072,727)	$ (2,825,454)	$ (1,776,000)
Lifetime Operational Hours	15600	15600	15600	15600
Production Time (hours), 1 Part	9	6	61.5	61.5
Parts Printed Over Lifetime	1733.3	2600	253.7	253.7
CE Ratio (dollars per part produced)	$ 558.88	$ 3,104.89	$ 11,138.81	$ 7,001.54

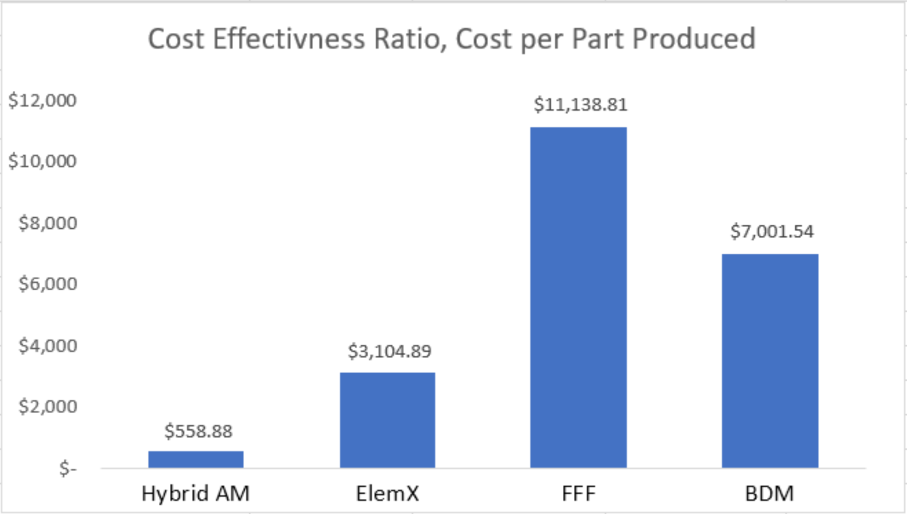


Figure 17. Cost Effectiveness Ratio, Cost per Part Produced

The hybrid 3D, status quo system shows a clear cost-effectiveness advantage over the three alternative production processes. Despite the significant cost differential between the ElemX and the other processes, the production speed of the liquid metal technology mitigates a large amount of the cost burden associated with the process. While FFF and BDM were assigned equal production rates (along with equal lifetime production hours), the cheaper BDM technology produced a significant differential in CE ratio between the two methods. This cost differential is primarily accounted for by the lack of a debinding wash station. Although the wash step is not part of BDM, recall the production times were equalized to account for longer sintering time. If the additional sintering time was shorter than the equivalent FFF wash time, BDM would show an even greater CE ratio differential from FFF. A summary of the results by CE rank is shown in Table 19.

Table 19. Initial Analysis Results, Rankings by CE Ratio

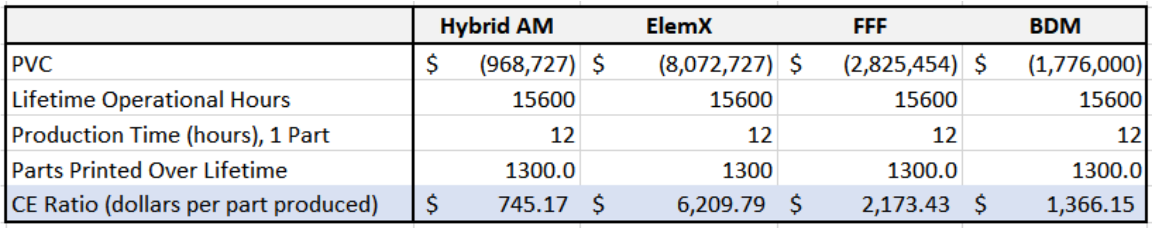
Printer (Process)	Ranking
3D Hybrid Solutions (WAAM)	1
Xerox ElemX (Liquid Metal)	2
Markforged Metal X (FFF)	4
Desktop Studio System 2 (BDM)	3

I. STEP 9: PERFORM SENSITIVITY ANALYSIS

A sensitivity analysis is conducted to test the strength and manner of influence that certain assumptions have on the results of the analysis. Because assumptions in a CEA are often “best guesses” due to lack of data (particularly in an *ex-ante* analysis), it is important to understand how changing those assumptions can affect the analysis (Cellini & Kee, 2010). Cellini and Kee describe two types of sensitivity analysis – partial and extreme case (Cellini & Kee, 2010). A partial sensitivity analysis is most useful when there are a limited number of assumptions and varies one assumption, parameter, or number at a time and holds all others constant (Cellini & Kee, 2010). An extreme case sensitivity analysis varies all parameters simultaneously to produce either a best-case or worst-case scenario (Cellini & Kee, 2010). Due to the limited number of parameters, a partial sensitivity analysis is used. The parameters varied in the sensitivity analysis are print/production times and lifetime operational hours (varied through yearly equipment usage rates and operating period durations). A summary of changes in printer rankings by CE ratio is shown in Table 26.

Varying the production times was addressed first. Although print times is a very important differentiator between processes, here the print times were equalized at 12 hours to highlight the influence of system price on the CE ratio. This 12-hour assumption was employed by Banks et al. (2020). Results of this adjustment are in Table 20 and Figure 18.

Table 20. Sensitivity Analysis, Equal 12-hour Production Time



	Hybrid AM	ElemX	FFF	BDM
PVC	$ (968,727)	$ (8,072,727)	$ (2,825,454)	$ (1,776,000)
Lifetime Operational Hours	15600	15600	15600	15600
Production Time (hours), 1 Part	12	12	12	12
Parts Printed Over Lifetime	1300.0	1300	1300.0	1300.0
CE Ratio (dollars per part produced)	$ 745.17	$ 6,209.79	$ 2,173.43	$ 1,366.15

Although a somewhat theoretical adjustment as the FFF and BDM processes are unlikely to complete full production in this time, the results are nevertheless illustrative of the effect that printer acquisition cost has on the CE ratio. The equalization of production times negates the ElemX's largest advantage over all other processes and makes the high per-printer price a significant downside to the process. Overall, equalizing the production times had a significant effect on the overall results.

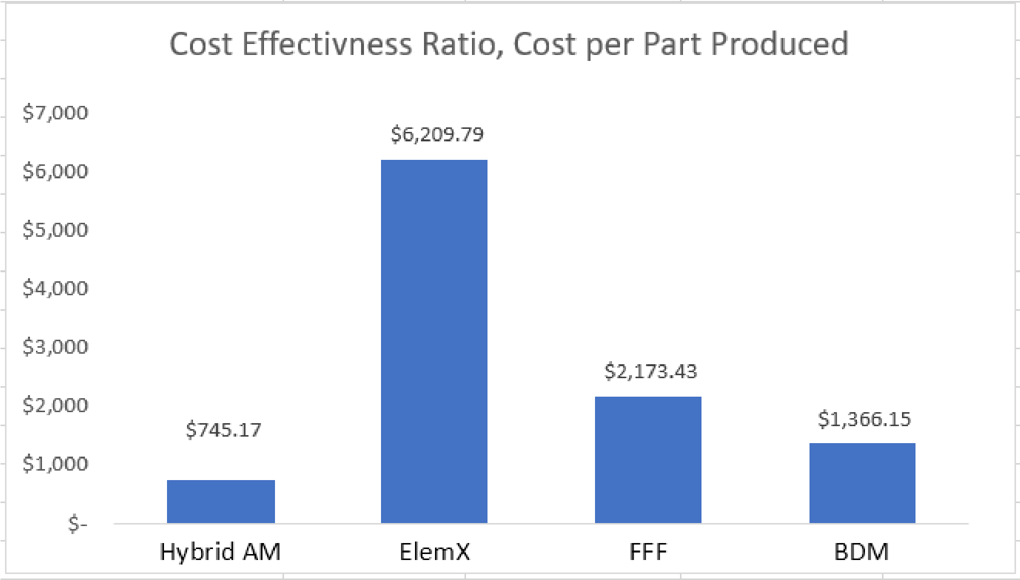
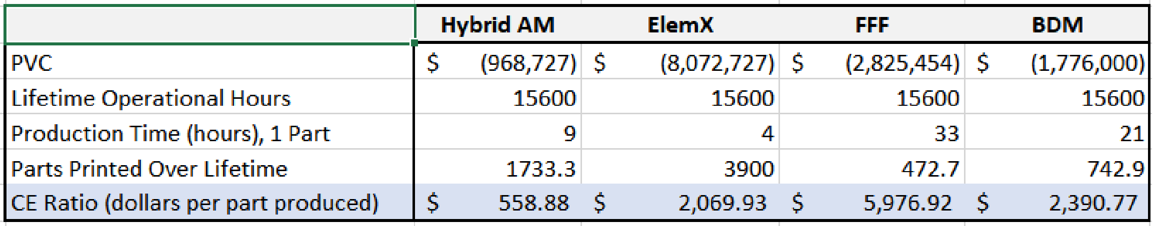


Figure 18. Sensitivity Analysis, Equal 12-hour Production Time

It is acknowledged that the 12-hour production time is unrealistic for some processes, as it may be either too fast or too slow depending on the process. The next sensitivity analysis performed set the production times to more feasible values. In this case, the hybrid AM process remained at 9 hours. The ElemX was reduced to the best-case scenario of 4 hours based on deposition rate and maximum build weight. FFF was reduced to the best-case scenario found in the cycle time data available from Markforged, which was the window hardware prototype production time of 33 hours. BDM used the same window hardware prototype cycle times but was granted the theoretical advantage of zero wash time (eliminating a 12-hour wash) and an equal sintering time to FFF resulting in a production time of 21 hours. The results of this production time variation are shown in Table 21 and Figure 19.

Table 21. Sensitivity Analysis, Best-case Scenario Production Times



	Hybrid AM	ElemX	FFF	BDM
PVC	$ (968,727)	$ (8,072,727)	$ (2,825,454)	$ (1,776,000)
Lifetime Operational Hours	15600	15600	15600	15600
Production Time (hours), 1 Part	9	4	33	21
Parts Printed Over Lifetime	1733.3	3900	472.7	742.9
CE Ratio (dollars per part produced)	$ 558.88	$ 2,069.93	$ 5,976.92	$ 2,390.77

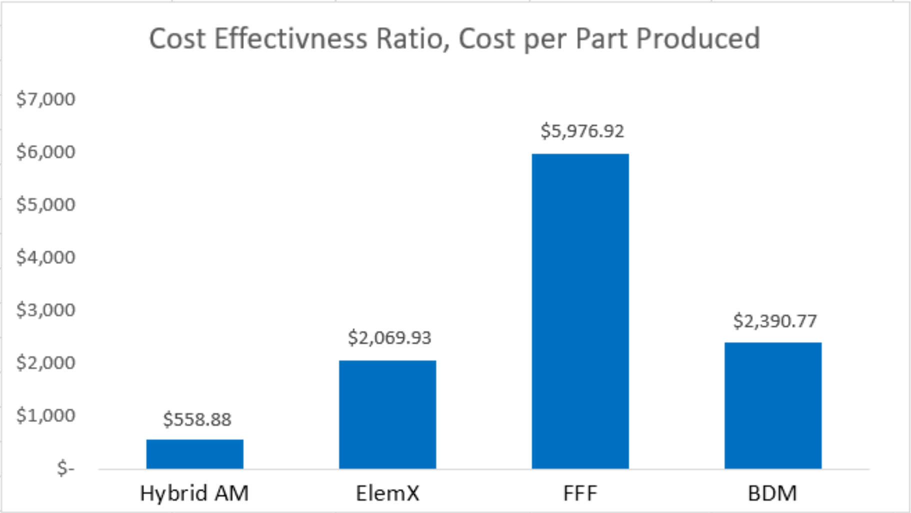
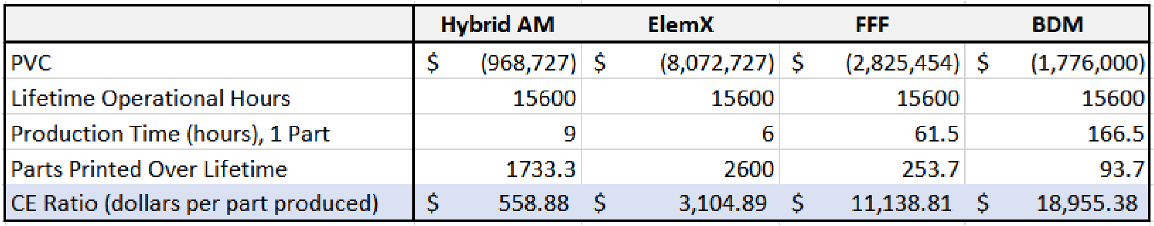


Figure 19. Sensitivity Analysis, Best-Case Scenario Production Times

The best-case scenario production times revert the outcome rankings back to the same outcome as the initial analysis, albeit with different CE ratios.

The final production time sensitivity analysis is based on Markforged’s assertation that, without a debinding wash, BDM sinter times are “6 to 10 times slower” (MF, n.d.a., p.7). To err on the conservative side of this argument, a sintering time six times slower than FFF was applied to the BDM production time. The BDM production time calculations used a wash time of zero and the mean process values from Table 16, resulting in a total production time of 166.5 hours. All other printer times remained unchanged. The results from a slower BDM process are shown in Table 22 and Figure 20.

Table 22. Sensitivity Analysis, Slow BDM Sintering Time



	Hybrid AM	ElemX	FFF	BDM
PVC	$ (968,727)	$ (8,072,727)	$ (2,825,454)	$ (1,776,000)
Lifetime Operational Hours	15600	15600	15600	15600
Production Time (hours), 1 Part	9	6	61.5	166.5
Parts Printed Over Lifetime	1733.3	2600	253.7	93.7
CE Ratio (dollars per part produced)	$ 558.88	$ 3,104.89	$ 11,138.81	$ 18,955.38

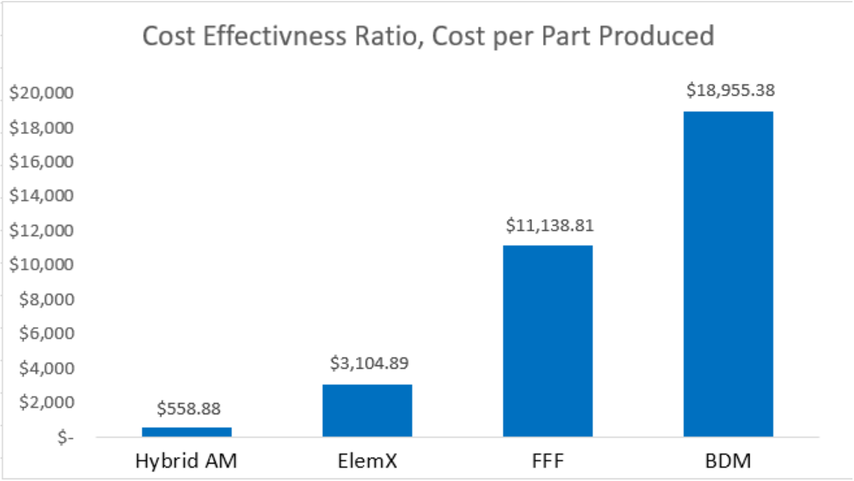
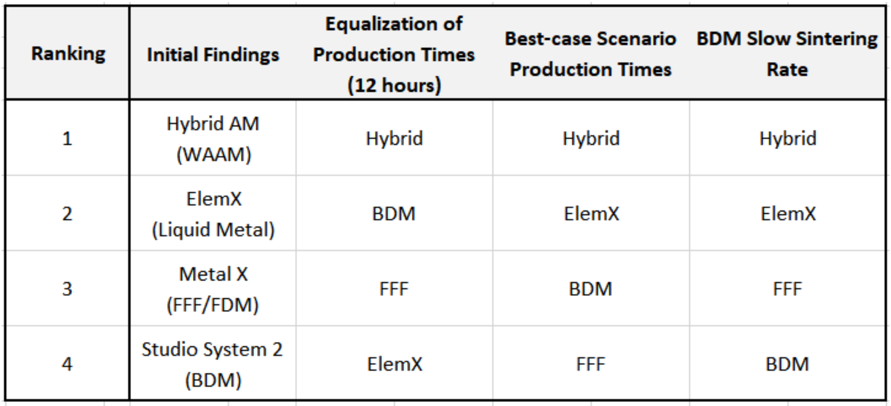


Figure 20. Sensitivity Analysis, Slow BDM Sintering Time

The slower sintering time had a significant effect on the CE ratio, placing the BDM process definitively behind FFF. While the change in CE ratio is dramatic (nearly tripling, increasing from $7,001.54 per part produced to $18,955.38 per part produced), the slow sintering time could be mitigated by the sinter furnace's ability to perform batch sintering of multiple parts simultaneously.

The adjustment of production times as a sensitivity analysis illustrated the influence that print time has on the cost-effectiveness of a printer. This result matches Daughtery and Heiple's conclusion that print speed has "most drastic impact on net present value" (Daugherty & Heiple, 2017, p. 82-83). A summary of the results of production time sensitivity analysis are shown in Table 23. The advantage that the hybrid AM system maintained through low system cost and the second fastest production time was unable to be overcome in any circumstance evaluated.

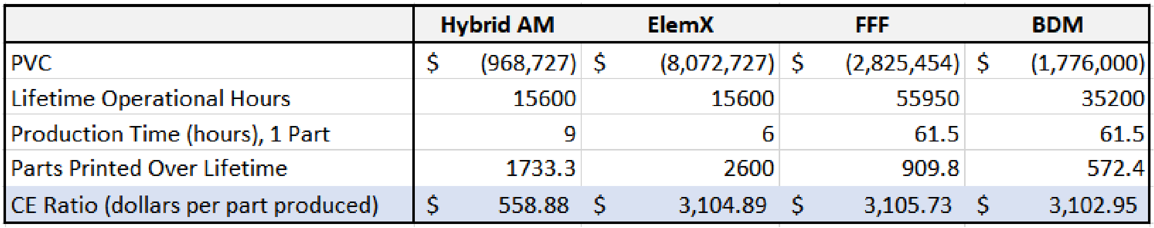
Table 23. Summary of Sensitivity Analysis Results, by CE Ratio Ranking



Ranking	Initial Findings	Equalization of Production Times (12 hours)	Best-case Scenario Production Times	BDM Slow Sintering Rate
1	Hybrid AM (WAAM)	Hybrid	Hybrid	Hybrid
2	ElemX (Liquid Metal)	BDM	ElemX	ElemX
3	Metal X (FFF/FDM)	FFF	BDM	FFF
4	Studio System 2 (BDM)	ElemX	FFF	BDM

The final sensitivity analysis performed examined the lifetime operational hours required for FFF and BDM to approximately equal the ElemX CE ratio. No attempt was made to have ElemX, FFF, or BDM equal hybrid AM as the hybrid CE ratio is so much lower than the alternatives that any adjustment to lifetime operational hours would likely be excessively unrealistic. Thus, having FFF and BDM equal ElemX, while still a significant gap to close, was considered a more worthwhile analysis. CE ratios were brought into near equality through the manipulation of lifetime operational hours. The results of the equalized CE ratios are shown in Table 24 and Figure 21.

Table 24. Sensitivity Analysis, Equalized CE Ratios



	Hybrid AM	ElemX	FFF	BDM
PVC	$ (968,727)	$ (8,072,727)	$ (2,825,454)	$ (1,776,000)
Lifetime Operational Hours	15600	15600	55950	35200
Production Time (hours), 1 Part	9	6	61.5	61.5
Parts Printed Over Lifetime	1733.3	2600	909.8	572.4
CE Ratio (dollars per part produced)	$ 558.88	$ 3,104.89	$ 3,105.73	$ 3,102.95

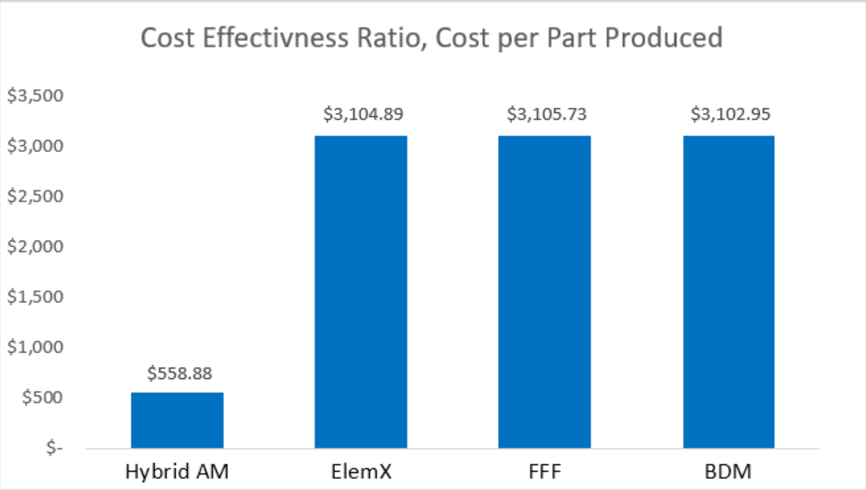


Figure 21. Sensitivity Analysis, Equalized CE Ratios

Through manual iteration, a near equalization of CE ratios between ElemX, FFF, and BDM was achieved. This equalization required significant increases in lifetime operational hours for FFF and BDM processes. The implications of the increase in lifetime operational hours are worth considering, as these hours imply increased workload on the machinery and operators. The implications of the increase in lifetime hours are shown in Table 25.

Table 25. Increase in Lifetime Operational Hours Breakdown

	Lifetime Hours	Hours Per Year	Hours Per Week	Hours Per Day	Parts Per Hour
Hybrid AM	15600.0	3120.0	60.0	12.0	1.0
ElemX	15600.0	3120.0	60.0	12.0	1.0
FFF	55950.0	11190.0	215.2	43.0	3.6
BDM	35200.0	7040.0	135.4	27.1	2.3

As seen in Table 25, the implications of arbitrarily increasing lifetime operational hours to achieve CE ratio equality results in infeasible solutions for both FFF and BDM, with FFF requiring 43 hours per day of operation and BDM requiring 27.1 hours per day. Accepting this impossibility momentarily, the production rate of 3.6 parts per hour for FFF and 2.3 parts per hour for BDM are infeasibly high rates, also.

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VI. CONCLUSION AND RECOMMENDATIONS

This chapter presents research conclusions, recommendations, and suggested areas for future work. Through examination of operational concepts, metal AM process attributes, and the conduct of a cost-effectiveness analysis, the hybrid AM process was found to the be preferred method for expeditionary employment by the Marine Corps. Hybrid AM offers a superior cost-effectiveness ratio in terms of cost per part over a five-year operational lifetime, along with a more versatile process which can be readily adapted to mission requirements.

A. CONCLUSION

This thesis examined how metal AM integrates with and supports the current operational concepts being developed and employed by the Marine Corps. Through an examination of literature covering AM in expeditionary environments, key benefits of AM were uncovered, including reductions in cost, waste, and logistical supply lines, along with an expected increase in operational readiness and correlated increase in operational effectiveness. Recommended attributes of an expeditionary AM system were examined for incorporation into the analysis, with two significant attributes identified being feedstock properties (e.g., availability and stability) and durability/deployability of AM machines. The importance of print speed on the effectiveness of an AM system was also discussed.

Through examining the literature regarding employment models, the general concept underlying the TACFAB and XFAB was validated. These systems offer constant AM presence for deployed Marine forces, with the ubiquity of the TACFAB providing "first line of defense," polymer-only AM capabilities for all units. When required by the tactical situation, the introduction of the XFAB, with more robust design and production capabilities, adds a second, more capable layer to the AM network. While the XFAB is fielded in smaller numbers than the TACFAB, the XFAB can focus on production of parts not possible with the TACFAB, such as metal parts or parts that do not have an existing, approved design resident in a central digital repository. With the concept of TACFAB and

XFAB found to be sound, the focus could then turn to the individual systems inside of the XFAB.

Four processes were considered, each represented by a single manufacturer and model of printer: Hybrid AM with Wire-Arc Additive Manufacturing from 3D Hybrid Solutions; liquid metal printing with the Xerox ElemX; fused filament fabrication with the Markforged Metal X; and bound metal deposition with the Desktop Metal Studio System 2. While the XFAB offered constraints on these four systems, primarily in terms of physical footprint, no system was immediate excluded from consideration, as even if a metal system could not fit inside the XFAB, the goal was to identify the best candidate systems for eventual adoption.

These four processes were evaluated using a nine-step cost-effectiveness analysis that used printer system price (dollars) and a quantification of benefits (parts produced over a system lifetime) to produce a cost-effectiveness ratio. This cost-effectiveness ratio allowed for comparison between alternatives using a common metric. As the USMC has some experimental operational experience with the 3D Hybrid Solutions WAAM equipment, this system was chosen as the status quo, rather than comparing candidate systems against the absence of metal AM printing. In all cases, including four sensitivity analyses, the hybrid AM system had a preferred CE ratio to all other systems, usually by a large margin. This CE ratio was heavily influenced by system acquisition cost and total production time; the hybrid AM system was the cheapest system to acquire and offered the second-fastest production time.

While the quantitative results were definitive in identifying a preferred process (hybrid AM), the hybrid AM system also offered qualitative benefits. Hybrid AM shows advantage in cost, print speed, and ability to machine to precision tolerances. All metal AM processes have differing precision capabilities, surface finishes, and other unique variations in the final product. Some of these variations, such as surface finish and tolerances, can be remedied using subtractive manufacturing (SM). This step is inherent and included in hybrid AM, and the process is developed knowing that final design specifications can be met in post-processing. This assumption and inclusion of the SM process in the hybrid AM system results in faster print times and faster cycle times. Hybrid AM, as offered by 3D

Hybrid Solutions, can print in a variety of expeditionary-relevant materials such as aluminum and stainless steel. Hybrid AM offers a more versatile process which can be readily adapted to mission requirements.

While the ElemX offers the fastest cycle times, the process (as currently available through Xerox) is limited to aluminum. While not an undesirable material, more metals would be beneficial as aluminum may not provide the required strength properties for a given application, thus making the metal AM capability operationally ineffective. Additionally, while the ElemX offers an advantage in cycle times, the high cost heavily influenced the CE ratio results. The ElemX's size also prohibits its direct integration into the XFAB container and would require its own stand-alone container for deployment and operation in theater. This process is already underway with the containerization of ElemX and operation aboard U.S. Navy amphibious shipping.

The FFF and BDM printers followed similar processes, with the primary differences between the two systems being BDM's cheaper system acquisition cost and BDM's lack of a debinding wash step. The lack of a debinding wash added significant time to the sintering process, though the cheaper system cost ultimately saw BDM have a preferred cost effectiveness ratio over FFF. Although both processes offer significant benefits in terms of a wide variety of printable metals, low risk/high stability of metal filament feedstock, and simplicity of operation, the processes also inherently carry additional limitations as they require extra equipment for post-processing. This equipment (furnace and wash for FFF, only furnace for BDM) adds cost and weight, and also occupies limited cubic footage within XFAB. Although this thesis did not include interior dimensional analysis of the XFAB, adding a metal FFF or BDM printer, wash station, and furnace will likely necessitate trade-offs in interior workspace or require removal of other AM capabilities. Additionally, FFF's use of a wash step also requires debinding solvent to be supplied and maintained with the XFAB, a requirement that no other process demands.

B. RECOMMENDATIONS

The hybrid AM process offers the highest cost effectiveness ratio as well as several qualitative benefits, such as compact equipment size, precision-tolerance capabilities, minimal PPE requirements, and minimal supply challenges (feedstock, shield gases, etc.). Given the superior cost effectiveness ratio, qualitative benefits, history of operational use in expeditionary environments, and existing integration in the XFAB, hybrid AM presents the best option for metal AM at the current time. However, hybrid 3D based on WAAM is not the singular, definitive expeditionary metal AM process; the other technologies offer unique benefits that may make them more useful under specific circumstances or better suited to producing a specific part, but these benefits are use-case specific and are ultimately unable to overcome hybrid AM’s cost and print speed advantage. Given the rate of technological advancement in metal AM and the five-year analysis period, it is recommended that metal AM system be re-analyzed after five years so that the Marine Corps can take advantage of system cost reductions and improved metal AM processes.

C. FUTURE WORK

This section contains recommendations for areas of future research that were encountered during research for this thesis. These recommendations were not able to be addressed in this research due to lack of data and time constraints.

1. Verification of Cost and Cycle Time Data

As discussed in Chapter IV, the cost and cycle time data used for this analysis was gathered from open-source information available from industry websites or printer manufacturers. This data represents the best data available given time constraints and allows for a complete cost-effectiveness analysis. However, the results would contain a higher degree of confidence if the cost parameters were derived from specific quotes from manufacturers; given that price is often contingent on contractual proceedings, a specific cost quote may be difficult to achieve. The next best alternative would be to have candidate manufacturers quote a specific production time for a unique part, standardized across all processes. It has been identified that print time is a significant, if not the most significant, parameter influencing cost effectiveness. Using verified production time data would ensure every candidate AM process is evaluated using a common “measuring stick.”

2. Queuing Model

A significant question driving the impact that metal AM can make in an operational environment is how many parts can be produced and fielded in a tactically relevant timeline. Stressing the limits of the production constraints are the demands for metal AM parts across a deployed force. The XFAB system is intended for deployment with an IMA capability, likely a USMC maintenance battalion, engineer support battalion, or combat logistics battalion. In any deployment scenario where the XFAB is employed, there may be only a handful of XFABs in theater at any given time. Given the size of a deployed force and equipment component failure rates relative to the quantity of metal AM machines, it is likely that the XFAB metal AM queue will quickly reach capacity. Understanding the quantity of XFABs to achieve a desired service level or the customer wait time for part production requests will help develop a more complete understanding of the true impact metal AM will have in an operational environment.

3. Lead Time Variability Reduction

AM has the potential to reduce part request lead time variance by eliminating the logistics downtime delays associated with the part requisition process. However, not all repair parts can be produced through AM and, even if production is possible, the AM network would be unable to meet demand if every repair part was required to be additively manufactured. Sourcing all repair parts through AM discards the economies of scale benefits offered by the traditional manufacturing and supply chain which has the ability to supply large volumes of parts at lower cost. These benefits are significant and should be preserved while AM is integrated into the repair parts supply chain. Thus, it becomes critical to ensure that only a certain, select group of parts are acquired through AM. Establishing a lead time “cut-off” heuristic would help preserve AM production capacity, in that a part would be sourced through AM only when the lead time exceeded a specified threshold, based on a risk tolerance level. This analysis would be especially relevant if applied to a hypothetical tactical scenario using XFAB production times, quantity of XFAB machines in theater, and real-world demand strength from a force of representative size and composition as may be deployed in future conflict.

4. Development of Military-Relevant Test Print

As discussed in Chapter IV, a challenge experienced in this research was the difficulty in comparing build rates/print times across varying types of metal AM processes. Some of this challenge is inherent in comparing different methods of AM, but this could be mitigated through an industry-accepted, standardized part design similar to “Benchy.” While “Benchy” is useful to characterization and calibration of printer capabilities, it may not be representative of the part attributes commonly required in military applications. Development of a standardized, military-relevant test print for characterization of AM printers and processes for military application would enable clearer comparison between printers and processes, facilitating acquisition and adoption decisions. This proposed test print could be used to inform risk tolerance in deployed environments. As noted by Van Bossuyt et al. (2013), risk-aversion or risk-seeking attitudes can influence how individuals will respond to risk. Though Van Bossuyt et al. focused specifically on individual engineer’s response to engineering risk, this risk tolerance or aversion may have a “trickle down” effect into the final part design which will be used to print in theater and installed on operational equipment. A standardized test print which can be verified and validated against certain risk levels in CONUS can then be used with confidence to verify AM printer performance and calibration in an expeditionary environment. This confirmation of print quality based on a standardized design can then provide an established and accepted level of engineering risk, leaving tactical commanders with only operational risk to consider when employing metal AM parts.

5. Definition of Use-Case Scenarios

This thesis emphasized the importance of operational context in the selection of a metal AM process. However, the operational context discussed was broad, generally examining distributed operations against near-peer competitors. Specific-use case scenarios of metal AM technology would further refine the envisioned application of metal AM and potentially eliminate some technologies. These eliminated technologies may be highly capable methods but may have a capability that exceeds Marine Corps' needs or envisioned use cases. The importance of understanding mission doctrine in conjunction with technological capability has been noted in the context of development of swarm unmanned aerial vehicle systems (Giles & Giammarco, 2019). As seen in the conflict in Ukraine, drones have established their military utility on the battlefield. An example of a specific use case employing metal AM could focus on the production of a casing for a fragmentation grenade deliverable by a drone or swarm of drones. In this use-case, print quality would factor much lower than print speed, which could significantly influence the choice of print process.

6. Selection and Training of AM Operators

Well-trained and proficient AM operators are essential to extracting maximum utility from any adopted AM process. Zelinski noted that AM sees its greatest benefits not just through preexisting training but when it is used by those interested in exploring the technology (2019). An innovative mindset allows for imaginative and diverse ideas for application of AM (Zelinski, 2019). While self-selection for AM is possible in some cases (e.g., incidental operators and volunteers for TACFAB training), for AM to have impact at scale, a formal curriculum is required. Complicating the training of operators is the technical nature of part design and application, the rate at which the technology advances and the other varied obligations that AM operators have as Marines (physical training, rifle qualifications, etc.). Gera et al. (2022) proposed a flexible, online/networked educational system that accommodates students' capabilities, learning styles, and availability. This structure may be well-suited for teaching AM skills to Marines, as it: offers short, intense, and focused modules; stimulates interest; integrates new information with pre-existing knowledge; provides personalized education with optimized content and delivery (Gera et al., 2022). Development of a modern educational system for AM that maximizes learner outcomes is essential for the technology to have the greatest operational impact.

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APPENDIX. AM PRINTER DATA

Table 26. Process Attribute Comparison, Printers Only.

AM Process	**Build Speed**	**Build Volume**	**Max Build Weight**	**Weight** (Printer)	**Ext. Dimensions** (Printer)
3D Hybrid Solutions (WAAM)	3.6kg/hr. (8lb/hr.) 35 in^3 /hr.	46x28x41cm (18x11x16in)	No data	No data	No data
ElemX (Liquid Metal)	0.5lb/hr. (0.23kg/hr.)	30x30x12cm (12x12x5in)	0.91kg (2lbs)	2146kg (4730lbs)	284x125x221cm (9 x 4 x 7 ft)
Metal X (FFF)	No data	30x22x180cm (12 x 9 x 7in)	10kg (22lbs)	75kg (165lbs)	56 x 46 x 112cm (22x18x44in)
Studio System 2 (BMD)	No data	30x20x20cm (12 x 8 x 8in)	6.5kg (14.3lbs)	97kg (214lbs)	95x82x53cm (37x32x21 in)

All dimensions and weights (except max build weight) rounded to nearest whole value. Data unable to be found or that does not directly fit the process is listed as “no data.” System data gathered from the following sources: H3D: Metal-AM (2019) & 3D Hybrid Solutions (n.d.); ElemX: Xerox (2021); Metal X: Markforged (n.d.d.); Studio System 2: Desktop Metal Inc. (n.d.b.).

Table 27. Process Attribute Comparison, Complete Systems.

AM Process	**Ext. Dimensions** (Wash)	**Weight** (Wash)	**Ext. Dimensions** (Furnace)	**Weight** (Furnace)	**Weight** (System)
3D Hybrid Sol. (WAAM)	N/A	N/A	N/A	N/A	No data
ElemX (Liquid Metal)	N/A	N/A	N/A	N/A	2146kg (4730 lbs.)
Metal X (FFF)	61 x 69 x 107cm (24 x 27 x 42in)	136kg (300 lbs.)	120 x 70 x 150 cm (47 x 28 x 59in)	350kg (772 lbs.)	561kg (1237 lbs.)
Studio System (BMD)	N/A	N/A	163 x 138 x 93cm (64 x 54 x 37 in)	733kg (1615 lbs.)	830kg (1829 lbs.)

All dimensions and weights rounded to nearest whole value. Data unable to be found or that does not directly fit the process listed as “no data.” Complete system weight includes printer and all post-processing equipment (as applicable). System data gathered from the following sources: H3D: Metal-AM (2019) & 3D Hybrid Solutions (n.d.); ElemX: Xerox (2021); Metal X: Markforged (n.d.d.); Studio System 2: Desktop Metal Inc. (n.d.b.).

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