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The Marine Corps has not identified metrics to measure return on investment (ROI). This paper will review the AM program and provide recommendations on appropriate metrics to use to inform commanders' decisions and measure return on investment (ROI), to support the Marine Corps' effort to leverage and continually improve the additive manufacturing program on the ground side. Recommend the development and implementation of metrics, which measure effectiveness in time, cost, and training to manage the AM program, evaluate ROI, and support commanders' decision making.

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Executive Summary

Title: Additive Manufacturing: Return on Investment Metrics

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Thesis: The Marine Corps has not identified metrics to measure return on investment (ROI). This paper will review the AM program and provide recommendations on appropriate metrics to use to inform commanders' decisions and measure return on investment (ROI), to support the Marine Corps' effort to leverage and continually improve the additive manufacturing program on the ground side.

Discussion: Based on the Commandant's Planning Guidance (CPG), the Marine Corps must train to fight using mission command. The Marine Corps' training and equipment must foster decentralized execution of orders. Innovations and changes to doctrine need to emphasize support of distributed operations (DO). The warfighter's logistics demands become more challenging in a DO environment. As such, leveraging technologies like AM increases flexibility and provides numerous options for support. In order to perform with the necessary agility and flexibility that the Commandant envisions, the Marine Corps must leverage emerging technologies. DO, in particular, demands new ways of thinking and performance from logisticians. As presented in this paper, using expeditionary 3D printers provides opportunities for innovation, ingenuity, and self-reliance in environments where time trumps cost, such as during times of conflict. As such, the Marine Corps must continue to explore and exploit AM to ensure it provides the greatest value to the Marine Forces. Since the initial implementation of AM in 2016, the Marine Corps has not identified metrics to measure return on investment (ROI). Metrics provide senior leaders with the ability to demonstrate ROI through the validation of effectiveness, which can affect future funding.

Conclusion: Recommend the development and implementation of metrics, which measure effectiveness in time, cost, and training to manage the AM program, evaluate ROI, and support commanders' decision making.

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I. Introduction

As the Marine Corps explores conceptual strategies like Sea Basing, Expeditionary Amphibious Base Operations, and Distributed Operations, one thing clearly stands out; building iron mountains for logistics support will not feasibly work during a war. The Commandant of the Marine Corps, General David H. Berger, has directed the transformation of the service to an agile, flexible, and lethal force ready to respond to the nation's call at any time. As detailed in the Commandant's Planning Guidance (CPG), to achieve this transformation, the Marine Corps must modernize its capabilities and adjust its organizational design.[1] Modernization will include leveraging technologies such as additive manufacturing (AM), artificial intelligence (AI), nanotechnology, quantum computing, and robotics.[2]

Since the initial implementation of AM in 2016, the Marine Corps has seen tangible gains stemming from the AM program. Examples of gains resulted in cost savings or time savings improving effectiveness. However, the Marine Corps has not identified metrics to assess areas of improvement or capitalize on successes within the AM program. Developing and using metrics can serve to inform senior leaders on how to proceed with the AM program to modernize the Marine Corps and improve logistical support. This paper will review the AM program and provide recommendations on appropriate metrics to use to inform commanders' decisions and measure return on investment (ROI), to support the Marine Corps' effort to leverage and continually improve the additive manufacturing program on the ground side.

Additive manufacturing can help to facilitate improved logistical support in Distributed Operations (DO). Carl von Clausewitz characterized war as inherently chaotic and hectic. The

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[1] David H. Berger, *Commandant's Planning Guidance* (United States Marine Corps, 2019), 11.
[2] David H. Berger, *Commandant's Planning Guidance* (United States Marine Corps, 2019), 12-13.

best plan breaks down upon crossing the line of departure. In order to combat friction, fog of war, and uncertainty leaders must incorporate as much flexibility, logistical austerity, and simplicity as possible into each plan. As the United States Marine Corps diligently prepares for the next fight, it must carefully assess every area for potential improvements. For much of the last two decades, the Marine Corps has functioned as a second land army. The first step requires returning to its amphibious roots in partnership with the Navy in order to concentrate its efforts on securing sea lines of communication and the world's littorals. To accomplish this task, the Marine Corps must enhance its DO capabilities by increasing its flexibility to support the Nation's military and foreign policy objectives. Distributed operations provide flexibility in accomplishing strategic objectives as they provide adaptable means to employ the forces; therefore, it calls for capabilities that must be sustained.

Distributed Operations environments increase logistical challenges when compared to centralized operations. To combat these challenges, the Marine Corps needs to work with what it currently possesses while incorporating opportunities in the future to gain lethality faster than adversaries. Marine Corps logistics must support a commander's ability to create tempo that can disturb the enemy's progress and help break its will. In order to extend its logistical reach during DO, it is imperative that the supply chain maximizes opportunities to increase flexibility, austerity, and simplicity. Supply containers containing repair parts and supplies, commonly referred to as Class IX-Blocks, present an example of how AM can supplement the supply chain and help extend the logistical reach. Class IX-Blocks have a finite amount of space. The use of expeditionary 3D printers provides opportunities for innovation, ingenuity, and self-reliance in environments where time trumps cost, such as during times of conflict. The expeditionary opportunities and benefits of AM have incalculable value as they have the potential to directly impact lives and mission success. As such, the Marine Corps needs to set the conditions to develop and evaluate metrics that enhance the AM program and allow commanders to leverage AM in both garrison and expeditionary environments in keeping with the Commandant's intent to "modernize our capabilities."[3]

II. Literature Review

Distributed Operations:

Modernization represents a critical component of the Marine Corps' move toward developing capable Distributed Operations (DO) forces. Distributed Operations "describes an operating approach that will create an advantage over an adversary through the deliberate use of separation and coordinated, interdependent, tactical actions enabled by increased access to functional support, as well as by enhanced combat capabilities at the small-unit level."[4] In a DO environment, command and control along with logistics support becomes increasingly challenging. New ways of thinking and innovation must be at the forefront while preparing for DO. As a start, a key requirement for advancing DO capabilities will be the further development of professional military education (PME) and training for individual Marines and small-unit leaders.[5] Each Marine at junior levels must now and in the future be able to possess a level of competence and broad understanding historically expected at higher ranks. Educating Marines with an understanding of the implications at the operational level while executing at the tactical level facilitates mission command in DO. The employment of DO calls for capabilities that

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[3] David H. Berger, *Commandant's Planning Guidance* (United States Marine Corps, 2019), 11.
[4] Michael W. Hagee, *A Concept for Distributed Operations*, (United States Marine Corps, 2005), V.
[5] Michael W. Hagee, *A Concept for Distributed Operations*, (United States Marine Corps, 2005), V.

spread across the seven warfighting functions: command and control, fires, force protection, information, intelligence, logistics, and maneuver.[6] Particularly in logistics, the dispersion of forces and resources requires innovative combat logistics support, principally in health services, maintenance, and supply. Of note, the supply chain must remain extremely flexible, adaptive, and scalable.[7] The use of AM can be scalable, flexible, and adaptive thus facilitating improved DO.

Additive Manufacturing Background:

In 2016, the Marine Corps adopted Additive Manufacturing (AM) in an effort to improve the effectiveness of logistics operations. AM, also known as three-dimensional (3D) printing, exemplifies a revolutionary process of sending product data to a printer that will fabricate a physical object. AM works with a printer that reads program design data, interprets the data, and layer by layer builds a product from bottom to top in an additive process. Users adjust the data to meet desired expectations and disrupt the landscape of manufacturing. Manufacturing tends to be associated with developing products from raw materials, through hand labor or often using large machinery, and industrial mass production. AM represents an emerging technology that revolutionizes the manufacturing of spare parts and other supply requirements for the Marine Corps.

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[6] Michael W. Hagee, *A Concept for Distributed Operations*, (United States Marine Corps, 2005), VI.

[7] Michael W. Hagee, *A Concept for Distributed Operations*, (United States Marine Corps, 2005), VII.

The technology that led to AM was developed over thirty years ago.[8] In its infancy the products developed through AM were inefficient and time consuming to develop. In AM, the process used for layering utilizes one of seven techniques: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization (see Figure 1).[9] As technology continues to evolve the production has improved with decreased time and cost. The improvements in AM have resulted in rapidly increasing use of the technology. The private sector and military have delved into this growing technology optimistically aware of the revolutionary promise AM brings to the supply chain. The Office of Naval Research, Science, and Technology (ONR) currently explores novel and new methods to understand and develop AM manufacturing processes and materials for naval applications. Improvements in digital manufacturing and digital design, along with computational modeling and simulation showcase an evolving landscape.[10]

[8] William H. Phillips, *Additive Manufacturing: Opportunities, Challenges, Implications*. (New York: Nova Science Publishers, Inc., 2016), 11.
[9] Interview with Captain Matthew Audette, Marine Corps Systems Command, Additive Manufacturing Cell on 13 Sep 2019 at Georgia Technical Research Institute. Quantico, VA.
[10] Office of Naval Research Science and Technology, *Materials and Processes for Additive Manufacturing*. Retrieved from www.onr.navy.mil/en/science-technology/departments/code-33/all -programs/332-naval-materials/additive-manufacturing.

AM Technology	Definition	Common Name	Abbr.	Example of Use
Binder Jetting	A process in which a liquid bonding agent is selectively deposited to join powder materials	Binder Jetting	BJ	(1) in Quantico, owned by AMOC Ex: HIMARS DVE Bracket.
Direct Energy Deposition	A process in which focused thermal energy is used to fuse materials by melting as they are being deposited	Laser Engineering Net Shaping Electron Beam Additive Manufacturing Rapid Plasma Deposition	LENS EBAM RPD	Wire fed metal printers are being used in the Maintenance Battalions. Ex: HIMARS folding antenna bracket.
Material Extrusion	A process in which material is selectively dispensed through a nozzle or orifice	Fused Deposition Modeling Fused Filament Fabrication	FDM FFF	300+ printers in the fleet. Ex: ECU vent cover, mic covers, MEP generator load stud wrenches, AAV-P7 throttle linkage.
Material Jetting	A process in which droplets of build material are selectively deposited	Material Jetting Nano Particle Jetting Drop on Demand	MJ NPJ DOD	Not used on the ground side. Used in the aviation side under the code name "cold spray."
Powder Bed Fusion	A process in which thermal energy selectively fuses regions of a powder bed	Multi Jet Fusion Selective Laser Sintering Selective Laser Melting Direct Metal Laser Melting Electron Beam Melting	MJF SLS SLM DMLM EBM	SLM metal powder bed printers are in use at the depots. Ex: MAC-50 crane shive.
Sheet Lamination	AM process in which sheets of material are bonded to form a part	Laminated Object Manufacturing	LOM	Not used. Old technology.
Vat Photopoly-merization	A process in which liquid photopolymer in a vat is selectively deposited	Stereolithography Digital Light Processing Continuous Digital Light Processing	SLA DLP CDLP	Not used. Attempted use but current state of the art leaves the machines too finicky and not expeditionary. The print materials are more sensitive to environmental effects.

Figure 1: Additive Manufacturing Processes. Source: Captain Matthew Audette

Department of Defense:

The Department of Defense (DOD) and other organizations (like America Makes) have worked to determine how to adopt AM throughout the DOD to enhance portions of the DOD's operations and mission.[11] Each service works autonomously to produce strategic implementation plans for AM.[12] The Government Accountability Office (GAO) submitted a report to Congressional Committees in October 2015 addressing Defense Additive Manufacturing. In the report the GAO found that the DOD has taken action toward the implementation of AM in an effort to advance combat capability and performance, and to realize cost savings.[13] The DOD concurred with the GAO's recommendation to "designate an Office of the Secretary of Defense lead to be responsible for developing and implementing an approach for systematically tracking department wide activities and resources, and results of these activities; and for disseminating these results to facilitate adoption of the technology across the department."[14] Assigning a lead to track information on AM facilitates DOD officials' abilities to obtain requisite information to leverage ongoing efforts.[15] Developing metrics for the Marine Corps to identify the ROI of AM directly feeds into this DOD determination to leverage ongoing AM efforts across the services.

MARADMINs:

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[11] United States Government Accountability Office. GAO Report 16-56 to Congressional Committees. Defense Additive Manufacturing: DOD Needs to Systematically Track Department-wide 3D Printing Efforts, pp 1-40.

[12] Defense Systems Information Analysis Center. Additive Manufacturing in the DOD. Retrieved from www.dsiac.org on 26 September 2019, 5.

[13] United States Government Accountability Office. GAO Report 16-56 to Congressional Committees. Defense Additive Manufacturing: DOD Needs to Systematically Track Department-wide 3D Printing Efforts, pp 1-40.

[14] United States Government Accountability Office. GAO Report 16-56 to Congressional Committees. Defense Additive Manufacturing: DOD Needs to Systematically Track Department-wide 3D Printing Efforts, pp 1-40.

[15] United States Government Accountability Office. GAO Report 16-56 to Congressional Committees. Defense Additive Manufacturing: DOD Needs to Systematically Track Department-wide 3D Printing Efforts, pp 1-40.

On 16 September 2016, the Marine Corps published the first Marine administrative message (MARADMIN) providing guidance and policy about the AM program. At the outset of the document, the message delineated a clear distinction between ground and aviation AM programs.[16] At the time, this message represented the sole source of guidance and policy provided to the Marine Forces for the implementation and management of AM. Ground units received guidance to forward details pertaining to AM, such as 3D design software, print files, materials, processes, and AM machines to Next Generation Logistics (NexLog). This message did not provide guidance pertaining to metrics or measurements of effectiveness. On 25 October 2017, Headquarters Marine Corps published the first update on the management and employment of AM. MARADMIN 594/17 expanded upon the approval process, placing the fabrication of AM items authority with the O-5 level commander, a Lieutenant Colonel at the battalion or squadron level. This allows commanders to assume the responsibility and risk associated with AM locally versus processing via a program office that awaits more risk adverse engineer approval. Furthermore, the message established the use of colored bins based on risk and the consequences of failure to designate AM parts, which served to expedite identification and approval. The message issued restrictions dealing with safety and legal matters. Once again, the message stipulated applicability to ground operations and designated Naval Air Systems Command (NAVAIR) as the authority postured to release guidance applicable to the manufacturing of aviation repair parts and components.[17] The message directed commanders to

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[16] Deputy Commandant, Installations and Logistics. *Interim Policy on the Use of Additive Manufacturing (3D Printing) in the Marine Corps.* MARADMIN 489/16, September 16, 2016, https://www.marines.mil/News/Messages/Messages-Display/Article/946720/interim-policy-on-the-use-of-additive-manufacturing-3d-printing-in-the-marine-c/

[17] Deputy Commandant, Installations and Logistics. *Headquarters Marine Corps Procedural Guidance Update on the Management and Employment of Additive Manufacturing*. MARADMIN 594/17, October 25, 2017, https://www.marines.mil/News/Messages/Messages-

maintain accountability of AM equipment, fabricated items, and material in Global Combat Support System-Marine Corps (GCSS-MC) or Defense Property Accountability System (DPAS) as applicable. This requirement for the collection of data denotes the first step toward developing metrics that assess the AM program's ROI.

MARADMIN 055/19, the second and most recent message, updated the Marine Forces with the status of the AM program and promulgated the plan of action and milestones for future implementation and policy plans. The message places emphasis on the use of the digital repository of record while communicating the intent to switch to a different system that allows joint usage and collaboration.[18] The Marine Maker website, located at https://innovatedefense.net/marine-maker, provides access to the Marine Corps' digital repository of record. MD5 hosts the information exchange portal (IEP), which the Office of the Secretary of Defense (OSD) sponsors. The site does not hold sensitive data or intellectual property; instead, commanders maintain such data locally.[19] The IEP serves as a starting point to hold AM information; however, a more robust and collaborative portal would improve the cooperation and management of AM.

Draft Marine Corps Order:

Display/Article/1353764/headquarters-marine-corps-procedural-guidance-update-on-the-management-and-empl/

[18] Deputy Commandant, Installations and Logistics. *Headquarters Marine Corps Procedural Guidance Update Number Two on the Management and Employment of Additive Manufacturing*. MARADMIN 055/19, January 30, 2019, https://www.marines.mil/News/Messages/Messages-Display/Article/1743680/headquarters-marine-corps-procedural-guidance-update-number-two-on-the-manageme/

[19] Interview with Captain Matthew Audette, Marine Corps Systems Command, Additive Manufacturing Cell on 13 Sep 2019 at Georgia Technical Research Institute. Quantico, VA.

In 2019, Headquarters Marine Corps developed a draft Marine Corps Order (MCO) addressing AM Policy. As of December 2019, this new MCO continues circulating through Headquarters Marine Corps and receiving feedback from senior leaders before the Deputy Commandant, Installations and Logistics (DC I&L), will receive it for his review and approval. The MCO will address commanders to "employ and advance additive manufacturing to its fullest extent possible in order to improve combat readiness in garrison and during expeditionary operations."[20] The order is organized into six chapters: Introduction, Implementation, Manufacturing Process, Aviation, Legal Considerations, and Training. The first chapter, Introduction, provides a general overview of AM by providing a broad overview of AM to ensure the reader understands the background and common language associated with this program. The second chapter, Implementation, covers authority within the AM program. Of note, the chapter delineates a clear distinction between the ground and aviation AM programs. The third chapter, Manufacturing Process, provides authoritative direction for ground equipment. Interestingly, this chapter addresses measures of effectiveness, which will serve to "capture AM metrics to determine manufacturing cycle time, throughput, and fill rates to assist in further analyzing the effects of the supply chain, maintenance production rates, labor hours, and facilities."[21] This section mentions some data collection via GCSS-MC but does not explicitly state how to evaluate, validate, or analyze the data. It also fails to specify who will accomplish this task. As senior leaders review and edit this order and as the digital repositories change, purposeful effort to retain and continually analyze the data collected will allow senior leaders to make adjustments to the program and continue to enhance its utility. Discussion among Marine

[20] Deputy Commandant, Installations and Logistics. *Additive Manufacturing Policy*, DRAFT MCO 4700.XXX, December 2019.
[21] Deputy Commandant, Installations and Logistics. *Additive Manufacturing Policy*, DRAFT MCO 4700.XXX, December 2019.

senior leaders over the need to develop metrics has occurred around Headquarters Marine Corps; however, they have not promulgated specific guidance or design of metrics.[22] The fourth chapter, Aviation, provides specific guidance applicable to Marine Corps Aviation. The section in this paper called AM in USMC-Aviation will further explore the status of AM within the aviation community. The fifth chapter, Legal Considerations, expands upon rights to technical data, intellectual property, and general legal concerns. Finally, the sixth chapter, Training, amplifies guidance on training standards, trainers, and curricula types.[23]

III. Additive Manufacturing in USMC-Ground

According to Captain M. R. Audette, Marine Corps Systems Command, Advanced Manufacturing Operations Cell, AM began as a priority to the 37th Commandant of the Marine Corps, General Robert B. Neller, and former Deputy Commandant, Installation and Logistics, Lieutenant General Michael G. Dana. They saw the utility and potential impact to logistics operations of the new technology. AM's implementation came from good faith efforts. It was seen as an experiment to enhance the source of supply and implement novel solutions. With the turnover of new senior leadership overseeing the program, questions over the programs' function, growth, and benefit stand out at the forefront.[24]

In 2016, the Marine Corps purchased its first 3D printer. As of 2019, all Marine Expeditionary Forces (MEFs) have 3D printers. The Marine Corps owns three industrial size

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[22] Interview with Master Sergeant Doug McCue, Additive Manufacturing Lead, Headquarters Marine Corps, Installations and Logistics on 16 Aug 2019 at Georgia Technical Research Institute. Quantico, VA.

[23] Deputy Commandant, Installations and Logistics. *Additive Manufacturing Policy*, DRAFT MCO 4700.XXX, December 2019.

[24] Interview with Captain Matthew Audette, Marine Corps Systems Command, Additive Manufacturing Cell on 13 Sep 2019 at Georgia Technical Research Institute. Quantico, VA.

printers capable of printing material derived from steel, aluminum, and nylon. Additionally, the Marine Corps owns five production size printers, which utilize metal injection molding, and over three-hundred desktop size printers that work using plastic. The Marine Corps has approved over 180 parts developed internally. The data repository has over 400 parts in inventory. Examples of 3D printed items include the following: Nibbler unmanned aerial vehicle (UAV), NATO slave cable covers, HMMWV door handles, MTVR dash vents, VSAT cap covers, MTVR side mirror shell, repair parts on power distribution boxes, and environmental control unit (ECU) duct covers.[25]

The DOD manages the affordable, timely, and effective issuance of systems to users through the Defense Acquisition System management process. An Acquisition Program is a "directed, funded effort that provides a new, improved, or continuing materiel, weapon, or information system or service capability in response to an approved need."[26] The Marine Corps has processed its AM program through the Defense Acquisition System. There are currently two programs of record for the AM program. A Program of Record is a "program as recorded in the Future Years Defense Program (FYDP) or as updated from the last FYDP by approved program documentation. It may also refer to a program that has successfully achieved formal program initiation, normally Milestone B."[27] The Expeditionary Fabrication (XFAB) is a funded program of record consisting of a mobile shelter with production grade printers. It is intended to be used by military occupational specialty (MOS) 2161 Machinists at Maintenance Battalions, Tank Battalions, and Amphibious Assault Vehicle Battalions to enhance the supply chain and

[25] Interview with Captain Matthew Audette, Marine Corps Systems Command, Additive Manufacturing Cell on 13 Sep 2019 at Georgia Technical Research Institute. Quantico, VA.
[26] United States Department of Defense. The Defense Acquisition System. DOD Directive 5000.01, August 31, 2018.
[27] DAU Glossary, Program of Record retrieved from https://www.dau.edu/glossary/Pages/Glossary.aspx#!both|P|28274

improve unit readiness. The Tactical Fabrication (TACFAB) is a FY20 program of record, intended to be used by every Marine Corps battalion to enhance the supply chain and unit readiness. It consists of two 3D printers and a laptop, which are stored in a Pelican case intended for expeditionary use.[28] The addition of AM equipment and trained personnel at the battalion level provide a much-needed level of self-sufficiency that would benefit logistical support in distributed operations.

Marine Corps Systems Command (MCSC) stood up the Advanced Manufacturing Operations Cell (AMOC) to manage the AM program. The AMOC has five missions to guide its efforts. First, it provide 24/7 fleet support. It manages the parts help desk and request for information phone line charged with providing 24/7 rapid response on 3D printing needs. Second, it provides both fleet and Program Management (PM) Liaison and Advocacy. The current policy for using AM parts is risk-based vise engineering and technical data-based. The AMOC provides the fleet with technical data for fielded designs that are not readily available to the fleet. The AMOC has direct access and open lines of communication with the labs holding the technical data, such as Naval Surface Warfare Center-Carderock Lab, John Hopkins University Applied Physics Lab, and Georgia Technical Research Institute. Furthermore, it can inquire about technical data and specifications. It also have funding for reverse engineering designs or conducting destructive testing. The AMOC serves as the liaison between the fleet, the program office managing the piece of equipment in question, and the technical experts. Third, it manages the digital repository and facilitates the parts approval pipeline, which consists of a step

[28] Interview with Captain Matthew Audette, Marine Corps Systems Command, Additive Manufacturing Cell on 13 Sep 2019 at Georgia Technical Research Institute. Quantico, VA.

by step concept to print process. Fourth, it manages the Marine Maker training program. Lastly, the AMOC assumes the responsibility of advancing the state of the art on battlefield AM.[29]

The AMOC oversees a large portion of the training of AM throughout the Marine Corps. The Marine Corps has the Marine Maker program to provide AM training across the fleet. The Marine Corps contracted a company called Building Momentum, headquartered in Alexandria, Virginia. It can facilitate training at any location requested by the Marine Corps. The AMOC coordinates providing the trainers, equipment, and supplies for training while the unit requesting the training is required to provide the space for the training and personnel to man it. Marine Maker will set up the space with the requisite equipment and materials. The requesting unit retains ownership of the maker space while agreeing to lend the space for future training. Use of the space is at the discretion of the unit commander. Most of these training spaces have been set up at Maintenance Battalions. During follow-on training sessions, the AMOC provides beginner or refresher training along with resupplies at no cost to the unit as MCSC funds this program. The training of personnel to conduct basic 3D printing requires about one day of instruction. Marine Maker contractors lead train-the-trainer courses and has to date trained most of the Marine Corps AM trainers consisting of over 30 trainers and over 2,000 trained Marines. The Marine Maker mobile team provides training in 3D printing, basic programming, computer-aided design (CAD), circuitry, robotics, and other rapid prototyping techniques. In addition to the Marine Maker training, which focuses on a wide range of rapid prototyping skills, each MEF has stood up and funded an AM Training Center (AMTC). The AMTCs primarily focus on training Marines specifically on CAD, 3D printing, and Marine Corps processes (part approval, IP issues, GCSS-MC, and AM use). The AMTC and a HQMC AM rep, currently MSgt Doug McCue,

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[29] Interview with Captain Matthew Audette, Marine Corps Systems Command, Additive Manufacturing Cell on 13 Sep 2019 at Georgia Technical Research Institute. Quantico, VA.

Additive Manufacturing Lead, Headquarters Marine Corps, Installations and Logistics, have a tri-MEF working group with a synced and approved program of instruction (POI) for the week-long Basic AM course. I MEF is testing POIs for a week-long Advanced Course, which focuses on advanced CAD, reverse engineering, and use of scanners.[30] While the Marine Corps has funded programs of record, established training, and approved POIs for AM, it has not established a formal training pipeline for AM across the service.

The Marine Corps does not have an occupational specialty formally trained in AM. As such, on the ground side the Marine Corps has leveraged MOS 2161- Machinist, as the skillsets of this MOS most closely resemble those required for AM. At this time, the Marine Corps has not taken steps to establish an "AM Marine" MOS; however, assessments of how to capture AM skillsets require further attention.[31] The Marine Corps should asses the feasibility of creating a secondary MOS to track personnel with AM skillsets. The Military Yearbook project provided the following billet description for MOS 2161- Machinist:

> Machinists perform various duties incident to fabrication, repair or modification of engineer, motor transport, weapons, and accessories. Duties include selection of proper stock and set up of work on lathes, shapes, milling machines, internal and external grinders, drill presses, saws and cylinder, or line-boring machines. Machinists work from sketches, diagrams, blueprints, written specifications, or oral instructions. The control of quality and accuracy is met by the machinists' use of precision measuring devices to include micrometers, vernier gauges, and various other gauges and the subsequent adjustment of machine tool controls. Fabrication of metals is also followed by welding with all standard welding equipment. Maintenance of all shop equipment is performed to ensure that serviceability is sustained. Coordination with other repair shops, reporting of work completion, and the shop administrative functions are requirements to be affected by machinists.[32]

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[30] Interview with Captain Matthew Audette, Marine Corps Systems Command, Additive Manufacturing Cell on 13 Sep 2019 at Georgia Technical Research Institute. Quantico, VA.
[31] Interview with Captain Matthew Audette, Marine Corps Systems Command, Additive Manufacturing Cell on 13 Sep 2019 at Georgia Technical Research Institute. Quantico, VA.
[32] The Military Yearbook Project. MOS 2161, Machinist. Retrieved from https://militaryyearbookproject.com/references/military-occupation-codes/usmc/field-21-ground-ordnance-maintenance/mos-2161-machinist

Marines of all occupational backgrounds are encouraged to conduct on-the-job training to gain skills and proficiency in the use of AM. Marine Maker conducts AM training at its headquarters or at any of the established Marine Maker locations within the fleet. To date, Marine Maker provides training at established spots at Marine Corps Base Camp Lejeune, Marine Corps Base Camp Pendleton, Marine Corps Air Ground Combat Center Twentynine Palms, and Camp Kinser. The AMOC desires to establish additional training sites in Marine Corps Base Hawaii, Camp Hansen in Okinawa, and Camp Johnson in North Carolina.[33]

IV. Additive Manufacturing in USMC-Aviation

Additive manufacturing is differentiated amongst the ground and aviation communities. Marine Aviation falls under the governance of the Deputy Commandant for Aviation (DC AVN). Furthermore, Marine Aviation follows the rules and regulations set forth by Naval Air Systems Command (NAVAIR) and Commander, Naval Air Forces (CNAF). Marine Aviation support comes from funding allocated to Naval Aviation commonly referred to as blue dollars. The Navy's budget funds blue dollars. According to the draft MCO on AM Policy, AM information processes dealing with Marine Aviation shall:

- Be pushed to the organizational, intermediate, and depot levels of maintenance.
- Be used at the manufacturing levels of maintenance (i.e. intermediate-level squadrons and depots.)

The focus of the organizational level will remain on improving maintenance performance and maintaining equipment and aircraft in mission capable status. The intermediate level will aim to

[33] Interview with Captain Matthew Audette, Marine Corps Systems Command, Additive Manufacturing Cell on 13 Sep 2019 at Georgia Technical Research Institute. Quantico, VA.

leverage AM to tackle the challenges caused by extended lead times or obsolescence that affect the organizational level end-state.[34]

Marine Corps Aviation uses exclusively the NAVAIR Joint Technical Data Integration (JTDI) repository website to manage aviation-specific AM data. DON aviation components, such as tools and job aids, reside exclusively on the JTDI website. Marines serving within aviation units that work with AM can leverage the JTDI website found at www.JTDI.mil to locate STL files for DON aviation parts and components. Furthermore, they can use the MILSUITE collaboration website located at HTTPS://WWW.MILSUITE.MIL/BOOK/GROUPS/MARINE-AVIATION-ADDITIVE-MANUFACTURING-MAAM to share lessons learned, best practices, and pertinent AM information.[35]

On the aviation side, the Marine Corps has relied on MOS 6044 - Aircraft Welder, as their skillsets best align with those required for AM.[36] The Military Year Book Project provided the following billet description for MOS: "Aircraft welders fabricate and repair aircraft metals through basic welding using the Gas/Tungsten/Arc/Welding (GTAW) process on aluminum alloys, steel alloys, stainless steel alloys, and precipitating hardening nickel-based alloys."[37] As with the ground side, the Marine Corps Aviation community encourages Marines of all occupational backgrounds to conduct on-the-job training to gain skills and proficiency. Aviation

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[34] Deputy Commandant, Installations and Logistics. *Additive Manufacturing Policy*, DRAFT MCO 4700.XXX, December 2019.
[35] Deputy Commandant, Installations and Logistics. *Additive Manufacturing Policy*, DRAFT MCO 4700.XXX, December 2019.
[36] Interview with Master Sergeant Doug McCue, Additive Manufacturing Lead, Headquarters Marine Corps, Installations and Logistics on 16 Aug 2019 at Georgia Technical Research Institute. Quantico, VA.
[37] The Military Yearbook Project. MOS 6043, Aircraft Welder. Retrieved from https://militaryyearbookproject.com/references/military-occupation-codes/usmc/field-60-aircraft-maintenance/mos-6043-aircraft-welder

Marines can leverage the same training opportunities as those available to ground Marines; however, they must follow the rules and regulations stipulated by NAVAIR for aviation-specific manufacturing. Although the ground and aviation AM programs are governed separately, it is important to be aware of each to get a holistic understanding of the implications for AM in the Marine Corps.

V. Implications for Additive Manufacturing in USMC

Advantages of AM:

From a supply management point of view AM represents the future of logistics. Moreover, the Marine Corps' quick adoption of AM facilitates the exploitation of its advantages. AM provides formidable benefits to the supply chain. The advantages of AM are reduction in time, reduction in cost, flexibility of design, and on-demand manufacturing at the point of need. Challenges in workforce development, trust to meet the required criteria, and quality assurance represent the key barriers to leveraging AM.[38] Figure 2 illustrates the opportunities and challenges that AM presents with relevance to the DOD.[39]

[38] Amanda M. Schrand. *Additive Manufacturing in the DOD.* Defense Systems Information Analysis Center. Fall 2018: Volume 5, Number 4.

[39] Amanda M. Schrand. *Additive Manufacturing in the DOD.* Defense Systems Information Analysis Center. Fall 2018: Volume 5, Number 4.

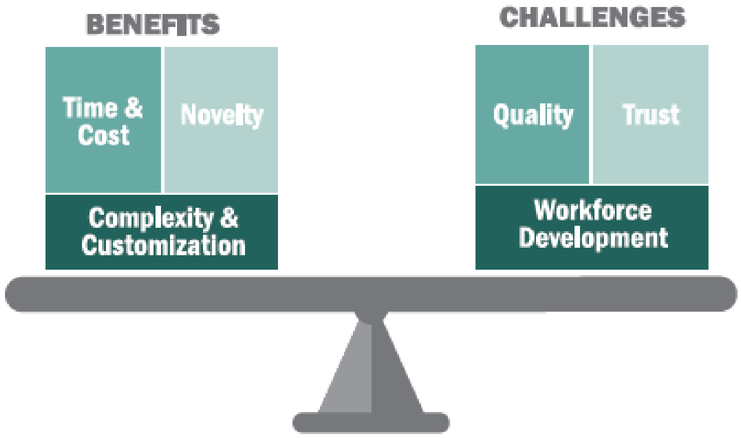

Figure 2: Opportunities and Challenges Presented by AM with Relevance to the DOD (Source: Schrand)

Time reduction is the first advantage of AM. At times when the end result contends between life or death, benefits are best weighed in time not cost. Receiving the required part in support of a mission that has Marines risking their lives takes greater value over the monetary value. AM can make a profound difference when resources must be obtained quickly. An advantage of AM comes from the speedy manufacturing of products or parts when compared to production utilizing traditional methods. Complex designs can be created as a CAD model and then transformed into a reality in a matter of hours. This delivers design ideas in a manner that allows them to be designed and verified in a short amount of time. The time saved over traditional methods changes the landscape as conventional manufacturing can take months to go from the design stage to prototype stage and right into the production process.

Cost reduction serves as a strong advocate of AM, providing a solid advantage. Although the cost of printers, associated equipment and supplies, along with training expenses front loads the expenditure to support the program; the long-term cost savings attributed to each fabricated item becomes one of the benefits of AM. The cost of printers, associated equipment, and supplies can be recouped through the cost savings of manufactured goods.[40] It is difficult to track the cost associated with novel solutions; however, the innovation, creativity, and overall problem solving has direct effects on the Marines' familiarization and proficiency that can pay dividends in austere conditions.[41]

Complexity and customization of design provide additional points of consideration, which the Marine Corps did not previously deliberate. AM has broadened the aperture of design thus pulling away from exclusive reliance on original equipment manufacturer (OEM) materials or geometries. Flexibility of design can pay dividends to a commander in cost, time, or both. Parts can be designed as a novel or preventive solution. A novel solution refers to an innovation to solve a problem. A novel solution can represent a temporary or creative fix to a part not available for a one-for-one correlation or swap with an already produced repair part. Illustrating an example of a novel solution, Transportation Support Battalion, 3rd Marine Logistics Group, developed a safety sign created out of plastic through AM to solve a Marine unit's vehicle identification problem.[42] AM lends itself to novel design techniques such as topological optimization that can produce the same part with less material and a reduced weight that traditional manufacturing cannot. In some instances where weight does not affect the integrity of the item, and can be reduced with no consequence, questions regarding the OEMs use of materials come to the forefront. For instance, can lighter materials be substituted- is this part aluminum because it bears a load that requires aluminum's strengths, or is it aluminum because it

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[40] Interview with Captain Matthew Audette, Marine Corps Systems Command, Additive Manufacturing Cell on 13 Sep 2019 at Georgia Technical Research Institute. Quantico, VA.
[41] Interview with Captain Matthew Audette, Marine Corps Systems Command, Additive Manufacturing Cell on 13 Sep 2019 at Georgia Technical Research Institute. Quantico, VA.
[42] Interview with Captain Matthew Audette, Marine Corps Systems Command, Additive Manufacturing Cell on 13 Sep 2019 at Georgia Technical Research Institute. Quantico, VA.

is the easiest metal to machine? Can a printed part be chopped carbon fiber and get 60-70% of the strength with one third of the weight?[43]

AM serves as an experiment to enhance the source of supply. Purchasing raw materials in bulk provides several benefits. To start with, units can supplement the source of supply locally. If the source of supply does not support a legacy item, the turnaround time exceeds mission requirements, or the cost of the item exceeds the budget, AM can serve as an option for a commander. Learning how to develop and print simple items tends to occur in a manner favoring the Marine Corps, with minimal time lost or materials wasted. Managing AM within the Marine Corps in garrison also provides benefits in the field. Specifically, familiarization with the equipment and increased proficiency result in training value that cannot be measured. Hyper local solutions can also be facilitated. For example, the sling mounting point covers on the hood of a HMMWV rust in highly corrosive locations such as Hawaii. This is not an issue in other parts of the fleet. Marines at MCB Hawaii have printed the covers in plastic to solve the corrosion problem.[44]

Challenges of AM:

The acceptance of risk or amount of risk that the Marine Corps chooses to accept represent the fundamental challenges of AM. Key challenges relate to quality, trust, and workforce development. Controls emplaced must assure compliance with safety and legal requirements along with rules and regulations of development, production, and use. Additionally, the Marine Corps has experienced challenges while attempting to obtain

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[43] Interview with Captain Matthew Audette, Marine Corps Systems Command, Additive Manufacturing Cell on 13 Sep 2019 at Georgia Technical Research Institute. Quantico, VA.
[44] Interview with Captain Matthew Audette, Marine Corps Systems Command, Additive Manufacturing Cell on 13 Sep 2019 at Georgia Technical Research Institute. Quantico, VA.

intellectual property for legacy parts or components from industry leaders. According to MSgt Doug McCue, the services have collaborated in an effort to negotiate with industry leaders the way forward with regards to intellectual property rights and warranty implications. The desired end state results in an arrangement between the DOD and private industry providing the military with requisite technical data.[45] The Marine Corps must start asking questions that were previously opaque due to the OEM handling of them as the Marine Corps tested systems as a system versus testing systems part by part. New questions like "how much does this one particular bracket hold? Why is this piece steel versus aluminum?" can serve to enhance the Marine Corps' understanding of the item and facilitate AM as an alternate solution.[46]

VI. Counter Argument

There are two main counter arguments against further investing or developing AM in the Marine Corps. First, a counter argument to investing in AM questions the difference between the costs incurred and risks undertaken in pursuit of this new technology versus the expected benefits and cost savings over time from not pursuing AM. This concern stems from the idea that AM is simply a different process not necessary a better process. Furthermore, since the Marine Corps is the smallest service in the DOD, there may be more value in having a larger organization, such as the Defense Logistics Agency (DLA), taking a larger role in developing this technology. Second, a counter argument to furthering the development of AM stems from the possible effects to the industrial base. Specifically, how the supply-chain will change as

[45] Interview with Master Sergeant Doug McCue, Additive Manufacturing Lead, Headquarters Marine Corps, Installations and Logistics on 16 Aug 2019 at Georgia Technical Research Institute. Quantico, VA.
[46] Interview with Captain Matthew Audette, Marine Corps Systems Command, Additive Manufacturing Cell on 13 Sep 2019 at Georgia Technical Research Institute. Quantico, VA.

fabricated items disrupt demand signals. In addressing these concerns, it must be understood that the value of AM can come from time saved, through less time to obtain an item but at a greater cost. Alternatively, sometimes value comes from obtaining an item at a lesser cost but decreased quality, which becomes a matter of risk tolerance or acceptance. The greatest benefit the Marine Corps gets from AM comes from improvements to readiness levels. AM allows commanders to solve maintenance problems and improve a unit's readiness, which in combat saves lives and supports mission accomplishment. The Marine Corps' intent with AM consists of augmenting the source of supply not replacing it.[47] The Marine Corps does not seek to become a source of supply or a manufacturing house; the Marine Corps aims to leverage AM to fix problems immediately and in austere environments.[48]

VII. Additive Manufacturing: Way Ahead

As stated in the CPG, the Marine Corps' "future force development must include appropriate prioritization of technologies, including AM."[49] Leveraging technological innovations to achieve and maintain military superiority has been a cornerstone of the United States military. Global basing has fostered military presence and global reach that support the National Strategy and promote enforcement of policy through military means when appropriate. The rise of near-peer adversaries challenges how the military prepares and postures for potential conflict. Continued efforts for technological innovations and advances have been paramount in

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[47] Interview with Master Sergeant Doug McCue, Additive Manufacturing Lead, Headquarters Marine Corps, Installations and Logistics on 16 Aug 2019 at Georgia Technical Research Institute. Quantico, VA.

[48] Interview with Captain Matthew Audette, Marine Corps Systems Command, Additive Manufacturing Cell on 13 Sep 2019 at Georgia Technical Research Institute. Quantico, VA.

[49] David H. Berger, *Commandant's Planning Guidance* (United States Marine Corps, 2019), 13.

military efforts. These initiatives have contributed to the military's ability to function in an environment of centralized command with decentralized execution.

AM has evolved tremendously over the last thirty years and continues to show promise of greater significance. The emergence and adaptation of AM both outlines and accompanies a new paradigm of how the Marine Corps handles logistics support. The Marine Corps' heavy investment in archaic equipment and processes inherently opposes change. Since the initial implementation of AM in 2016, the Marine Corps has seen tangible gains stemming from the AM program. As directed in the CPG, the Marine Corps needs to embrace new disruptive technologies and change how it currently operates. The future of the Marine Corps depends on the actions and cultural changes that are set now. The Marine Corps must develop metrics that inform commanders' decisions and measure ROI of the AM program as a means to effect change. Specifically, senior leadership should develop metrics which support the Marine Corps' effort to leverage and continually improve the additive manufacturing program on the ground side.

VIII. Recommended Metrics

The Marine Corps collects data from the ground and aviation AM programs; however, no direction has been promulgated to standardize and analyze data that can support senior leaders' decision making and enhancement of the AM program. Once published, the Draft MCO will serve to standardize the data collected.[50] This paper provided a background for both ground and aviation AM programs; however, the recommendations provided address the ground side as the

[50] Interview with Master Sergeant Doug McCue, Additive Manufacturing Lead, Headquarters Marine Corps, Installations and Logistics on 16 Aug 2019 at Georgia Technical Research Institute. Quantico, VA.

aviation side is governed by NAVAIR. In addition to collecting data, the Marine Corps needs to adopt metrics, which facilitate the evaluation and decision making of senior leaders. Furthermore, newly developed metrics ought to communicate AM benefits to Marine Forces and higher headquarters. Metrics for consideration include:

AM Fabricated Item:

- AM time (i.e. time to fabricate item) vs. cost time (i.e. wait time for item on order)
    - In time (#) (i.e. 1 day vs. 6 months)
    - End State: Analyze and evaluate the impact of AM on the readiness of major equipment. Support senior leaders determine effect of AM on unit readiness. For example, preventing a major end item from a six-month deadline through the AM of part X in 2 hours.
- Cost of manufactured item vs. retail cost of item
    - In dollar value ($)
    - End State: Analyze and evaluate the cost savings gained from AM. Support senior leaders making budgeting decision. For example, saved $17,000 through the AM of item X, which total cost consisted of $17,500 through the source of supply versus $300 through AM.
- Quantity of novel solutions vs. cost of novel solutions produced
    - In dollar value ($)
    - End State: Analyze and evaluate the cost of AM fabricated projects which produce preventive solutions. Further categorize by attribute (i.e. repair part, tool, training aid, safety aid, facilities, innovation) thus allowing senior leaders to assess utility of

AM in process improvements. For example, spent $300 in AM toward safety process improvements. Spent $300 in AM for tools.

- AM item fabrication date vs. AM item disposal date
  - In time (#)
  - End State: Analyze the life cycle of AM fabricated items. Support senior leaders in determining the durability and endurance of AM items when compared to traditionally manufactured like items. Additionally, support senior leaders in assessing adequacy or quality assurance controls.
- Total Number of CAD files maintained in repository each year
  - In quantity (#)
  - End State: Analyze and evaluate the number of CAD files created by Marines. Support senior leader's assessment of AM improvements to expeditionary operations. For example, how many CAD files can be used during DO; which enhance the supply chain in DO and austere environments.

AM Equipment:

- Time used/operational vs. time down/not operational
  - In time (#)
  - End State: Analyze and evaluate asset availability for use. Support senior leaders in determining equipment preferences based on contributing factors to operational status. For example, model A has a greater down time than model B when used in expeditionary environments.
- Total number of different parts printed vs. type of machine used
  - In quantity (#)

- End State: Analyze and evaluate the production per machine type. Support senior leaders in determining most commonly used machine by type to make decisions regarding effectiveness and efficiency of printers. For example, 200 different items printed using machine type A or 100 different items printed using machine type B.

AM Training:

- Personnel trained vs. personnel actively printing
  - In percentage (%)
  - End State: Analyze and evaluate the growth and employment of trained personnel. Support senior leaders assess the fleet's buy-in of AM. For example, over 2,000 personnel trained; however, estimating 100 personnel routinely AM items.

IX. Conclusion

The ability to react quickly to immediate logistics requirements in support of Marine forces generates tempo. As an organic asset of a unit, with adequate training and standardization of skill sets, the AM capability facilitates speedy logistical support in austere conditions. Ultimately, AM provides enhanced logistical capability to the commander with options that have direct impact on operational success in a contested environment. Based on the Commandant's guidance, the Marine Corps must train to fight using mission command. The Marine Corps' training and equipment must foster decentralized execution of orders. Innovations and changes to doctrine need to emphasize support of DO.

The warfighter's logistics demands become more challenging in a DO environment. As such, leveraging technologies like AM increases flexibility and provide numerous options for support. In order to perform with the necessary agility and flexibility that the Commandant envisions, the Marine Corps must leverage emerging technologies. Distributed operations, in particular, demands new ways of thinking and performance from logisticians. As presented in this paper, the benefits of AM speak for themselves and they speak loudly. As such, the Marine Corps must continue to explore and exploit AM to ensure it provides the greatest value to the Marine Forces. Metrics provide senior leaders with the ability to demonstrate ROI through the validation of effectiveness, which can affect future funding. Currently, no metrics exist to measure return on investment within the Marine Corps' AM program. Metrics that measure effectiveness in time, cost, and training need to be incorporated into the management of the program and evaluated to measure ROI.

X. Illustrations

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XI. Bibliography

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