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A SYSTEMS APPROACH TO ADDITIVE MANUFACTURING IN THE MARINE CORPS

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THESIS

A SYSTEMS APPROACH TO ADDITIVE MANUFACTURING IN THE MARINE CORPS

by

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September 2019

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A SYSTEMS APPROACH TO ADDITIVE MANUFACTURING IN THE MARINE CORPS

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ABSTRACT

Additive manufacturing (AM) is an emerging technology that has already proven useful to the Marine Corps. However, guidance regarding AM and structure for the organization of AM efforts in the Corps has lagged behind the real-time capabilities of this technology. This thesis examines current AM capabilities and current Marine Corps structure, policy, and guidance regarding the use of AM technology. A systems engineering approach is used to propose a path forward for the Marine Corps with regard to AM technology and force structure requirements, with the goal being to increase the efficiency and effectiveness of the Corps' use of AM technology.

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	three dimensional
AFRL	Air Force Research Laboratory
AM	Additive Manufacturing
AMOC	Advanced Manufacturing Operations Center
AVN	aviation
CAC	Common Access Card
CAD	computer aided design
CATC	combined arms training center
COA	course of action
D/NDT&E	destructive and/or non-destructive testing and evaluation
DC	deputy commandant
DLA	Defense Logistics Agency
DoD	Department of Defense
DoN	Depart of the Navy
DOTMLPF	doctrine, organization, training, materiel, leadership, personnel, facilities
FBSE	functions based systems engineering
FOUO	for official use only
GCSS-MC	Global Combat Support System – Marine Corps
HMMWV	High Mobility Multipurpose Wheeled Vehicle
HQ	headquarters
HQMC	USMC Headquarters
I&L	Installations and Logistics
JWICS	joint worldwide intelligence communications system
LOGCOM	USMC Logistics Command
LPV	logistics, planning, and vision
MARADMIN	Marine administrative notice
MCSC	Marine Corps Systems Command
MCWL	Marine Corps Warfighting Laboratory
MEF	Marine expeditionary force

MEU	Marine Expeditionary Unit
MOS	military occupational specialty
MTBF	mean time between failure
MTT	mobile training team
MTVR	medium tactical vehicle (replacement)
NAVAIR	Naval Air Systems Command
NEO	non-combatant evacuation operation
NEXLOG	Next Generation Logistics
NPS	Naval Postgraduate School
OEM	original equipment manufacturer
PEB	pre-expended bin
PEI	principal end item
RIA-JMTC	Rock Island Arsenal – Joint Manufacturing and Technology Center
RYG	red yellow green
SIPR	secret internet protocol router
SMR	source maintenance and recoverability
SQL	structured query language
SYSCOM	Marine Corps Systems Command
TDP	technical data package
TTR	time to repair
UI	user interface
USAF	United States Air Force
USMC	United States Marine Corps

I. INTRODUCTION

Additive manufacturing (AM), which includes the more specific technique commonly known as 3D printing, is an emerging technology that has already proven useful to the Marine Corps; however, guidance regarding AM and structure for the organization of AM methods in the Corps has lagged behind the development of this technology. In this thesis, current AM capabilities, current Marine Corps policy, guidance, and use of AM technology are examined. For purposes of this thesis, the terms “AM” and “3D printing” are used interchangeably, as the technology itself is largely indistinguishable. The difference between the two resides largely with the user. Additive manufacturing is an industrial process, whereas 3D printing is generally more consumer focused and smaller scale. The author has used both terms throughout the paper because the Marine Corps and other services utilize the technology on both scales, to produce large components at industrial capacity and speed, and to custom craft low volume devices or widgets at the using unit level to aid in their operations. A systems engineering approach is used to propose a path forward for the Marine Corps with regard to AM technology and force structure requirements with the objective being to increase the efficiency and effectiveness of the Corps’ use of AM technology. Currently, the Marine Corps is utilizing AM and continues to advance in materials, capability, and effectiveness concerning AM. It has installed printers on ships (MARADMIN 594/17, 2017), at maintenance battalions (MARADMIN 489/16, 2016), and at the depot level (MCSC, 2018). The Marine Corps has added 3D printers to the lists of equipment units can use their own budgets to purchase, and many have. 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. The Marine Corps is working on producing mobile printing labs (MCSC X-Fab Video 2017), increasing the types of materials they can use for printing, and expanding their library of printed parts. The Marine Corps has also largely settled questions regarding the legality of 3D printing parts that are otherwise provided by OEMs through contractual service and warranty obligations (Acosta, 2018a, 2018b). The Marine Corps has, at present, two organizations sharing the lead in AM: the NEXLOG AM Cell (which is a non permanent organization slated to disband in the near future) and the Marine Corps Systems Command (MCSC) Advanced Manufacturing Operations Cell (AMOC). The MCSC AMOC deals with AM as part of a larger slate of advanced manufacturing techniques but is also not part of a permanent structure, currently residing under the G-3 operations cell of MCSC. Thus, the issue still requires study in order to create a permanent and sustainable organizational structure for AM in the Marine Corps, which itself will aid the Marine Corps in increasing efficiency and scaling up AM utilization and capability. The Marine Corps is utilizing AM at present but can and should improve both the breadth and depth of AM utilization via permanent organizational structure designed to oversee that improvement over time.

A. OBJECTIVE AND RESEARCH METHOD

The purpose of this analysis was to conduct a systems engineering inspired analysis of the requisite processes and systems by which the Corps makes use of AM technology. It sought to identify and provide recommendations for a way forward for the Marine Corps with regard to AM technology, capabilities, and policy. This work addressed the following questions:

1. How does the Marine Corps currently utilize AM as a part of its logistics operations?

2. How should the Marine Corps organize itself to enable it to optimize AM to enhance war-fighting efficiency?

The research method used for this study was a qualitative review and subsequent Functions Based Systems Engineering (FBSE) approach to break down this complex system of systems. The research was conducted in three phases. Phase I was data collection through a comprehensive examination of literature and a site survey to the annual Navy and Marine Corps conference on AM. Phase II leveraged systems engineering techniques to conduct a functional analysis of the current utilization of AM in the Marine Corps and explain how that utilization could be expanded via DOTMLPF (doctrine, organization, training, materiel, leadership, personnel, and facilities) changes. Phase III was the development of an AM strategy for the future force.

B. PROPOSED DATA, OBSERVATION AND ANALYSIS METHODS

Relevant data was gathered through the literature review process. Systems engineering methodology was used to examine current AM use in the Marine Corps and potential increased usage made possible by various structure and policy changes.

C. PROBLEM AND PURPOSE STATEMENTS

At present, AM technology and its use falls under the standing Marine Corps logistics structure, (MCSC AMOC Brief, 2018) and lead organizations have put forth some guidance, instructions, and regulations concerning AM technology in the Corps. This work is predicated on the belief that a Systems Engineering approach can provide even greater achievement, safety, efficiency, and effectiveness for the future force. The Corps, to their credit, has been swift to adopt AM technology in order to decrease supply chain lengths, improve uptime of principle end items (PEIs), and decrease mean time-to-repair (MTTR). The Marine Corps has addressed many of the risks associated with the use of AM produced parts. Current Marine Corps guidance and regulations aim at mitigating these risks (MARADMIN 594/17, 2017). However, intuition suggests that with additional organizational structure the Corps can move beyond the basics of AM and truly utilize the depth of capability inherent in this technology for the benefit of the Corps long term. This effort takes a “system of systems” look at the overall structure of the Corps, as related to logistics and specifically AM, in order to determine whether, where, and how additional or modified organizational structure could work towards paving the way towards enhanced AM for logistics. One concern, as seen in current regulations, is the comparative safety of AM parts compared with Original Equipment Manufacturer (OEM) parts, especially critical parts, for PEIs. One basic assumption is that it is not enough to be merely manufacturing non-critical parts via AM. The Corps should be aggressive about comparison between critical AM and OEM parts, including destructive and non-destructive testing, in order to dramatically increase the breadth of parts able to be manufactured via AM for these uses. For example, the Marine Corps should write all contracts for new equipment such that they take into account AM capabilities and incentivize contractors who design devices with in-the-field AM in mind for repair.

There are multiple potential benefits of this research. With the right effort there is potential for the Corps to dramatically increase the percentage of parts the Corps can AM in the field (or at sea), further shortening or eliminating supply chains and decreasing MTTR while positively impacting mission readiness by reducing delays associated with the supply chain for PEIs. If the Corps develops the capability to safely employ AM mission critical parts, they can increase PEI related (including aircraft) uptime and availability. Similarly, if the Marine Corps produces more parts itself, they reduce dependence on the OEMs to provide maintenance, modification, and refresh. This has the added benefit of a commensurate reduction of contractors in the field, which would in turn allow the Corps to maintain its focus on warfighting. Furthermore, with increased AM capability, the Corps would be more mobile, as it is easier to source component material than finished parts. A unit stuck in a remote location would only need to source, as an example, a certain grade of plastic or steel of a certain density rather than a fully manufactured part amidst the chaos of battle. Lastly, the Corps will need a way to ensure the digital AM designs promulgated to the force are secure and have not been tampered with, at present the Corps does not have a system designed for that. At first Marine mechanics were sending each other digital AM designs via email, and now there is an externally managed (contracted to a third party) database that resides on the open internet and requires minimal credentialing and approval to access. Marines worldwide need to be able to trust parts that they have printed and commanders need to have a built in system with ability to provide risk information to AM users regarding the efficacy of AM parts. Lastly, should the Corps succeed in this endeavor their model can become the standard for the entire DoD—all the services are working through AM problems currently, but nobody has a fully integrated solution yet.

D. POTENTIAL BENEFITS

This research offers an opportunity for the Marine Corps to identify possible additional advantages available from continued use of additive manufacturing technology than can be realized with changes to force structure, guidance, and policy in the future. Chapter five recommends an AM strategy that can inform future USMC programs, structure changes, logistics, and contract policy. As the USMC continues to increase utilization of AM as a manufacturing technique available at all levels, permanent organizational structure dedicated to overseeing the way forward with this technology will improve both the breadth and depth of AM utilization and provide untold benefit for the future Corps.

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II. LITERATURE REVIEW

Although Additive Manufacturing (AM) has been around in some form since the early 1980s, it is only relatively recently that techniques and technology have matured enough to become more cost effective, faster, and capable of producing more intricate and exacting models. In 2013, the first personally affordable 3D printer was prototyped. Possible military applications of the technology were immediately recognized, as (even with the early model plastic only, small-scale printers) small non-critical parts could be rapidly fabricated and the technology continued to become more versatile in materials and capabilities over time. Zimmerman and Allen, in their 2013 NPS thesis, examined AM and reviewed how the three major process types (stereolithography, selective laser sintering, and fused deposition modeling) work, the materials with which items can be produced, and the build times for each process. They built an early list of the potential pros and cons of AM for the military. In 2014, Christopher O'Connor, in his NPS thesis, examined how the AM modalities were being used in the Navy, obstacles to wider implementation, and focused on how AM could be integrated into the Defense Logistics Agency (DLA). From his thesis, it is clear that the Navy was utilizing AM in workshops and labs as early as 2010, but these devices were large and quite specialized. In early 2013, two small plastic-capable printers were installed on two ships. He asserted that the Navy needs to push to better integrate AM capabilities into all levels of the supply chain and that DLA should be staffed and equipped to constantly build replacement parts in order to decrease the time lag from OEMs. In 2015, Luke J. McLearen looked at AM in the Marine Corps—at that time, no 3D printers were in direct use by Marines. McLearen examined current best options for commercially available 3D printers and the utility of those equipment options within the Marine Corps by using case scenarios that included analysis at the MEU, MEB, and depot level, and he explored potential future options as the technology matures. His conclusion, in essence, was that the Corps should first look to install and use AM technologies on ships with the MEU (in order to rapidly fabricate non-critical parts while underway, reducing MTTR and increasing up-time) and at the depot level (for rapid fabrication of non-critical parts in order to decrease time lag created by reliance on OEMs to replace these small parts and get them shipped to units in need). The Marine Corps has largely followed McLearen's recommendations, as the MEU and the depot level were indeed the first installations of AM technology in the Marine Corps.

In 2016, Matthew Friedell examined AM in the Marine Corps but with a focus on its applications in support of expeditionary operations. He addressed issues such as watermarking of digital models, the necessity of a secure repository of digital models, and concerns regarding on-site customization. If one can summarize McLearen as saying that the Corps should indeed purchase and use 3D printers, one can subsequently summarize Friedell as pointing out a few additional institutional needs and complications inherent in the continually evolving use thereof. In 2016, the Marine Corps released the first interim policy on the use of AM in the Corps (MARADMIN 489/16) that appointed the office of Deputy Commandant, Installations and Logistics (DC I&L), Logistics Policy as the HQMC AM team through the Next Generation Logistics (NEXLOG) initiative. The team includes members from Combat Development and Integration (CD&I), the Marine Corps Warfighting Lab (MCWL), Marine Corps Logistics Command (LOGCOM) and the Deputy Commandant for Aviation (DC AVN). This MARADMIN authorized commands to immediately begin the use of AM technology to produce repair parts with a source maintenance and recoverability (SMR) source code of M or X and maintenance codes commensurate with unit authorized levels of maintenance. Essentially, HQMC authorized units to produce (via AM) small, non-critical parts coded for unit level manufacture or those that the OEM no longer produces, which they are allowed by the technical manuals (TMs) to install at their level of maintenance. That is to say, this MARADMIN allows units to make (via AM) and install small non-critical parts that they would have had to manufacture or self-procure anyway and that their mechanics are already trained to install. The only thing that changed, really, was that instead of occasionally sourcing part manufacture out to shops (custom jobs) for parts no longer made, maintenance units could begin producing those parts themselves. Anything more involved, or related to the safety of the Principle End Item (PEI) in which it is installed, requires coordination with higher level commands legal office and written approval from the units commanding officer. The inclusion of the legal office in the process stems from the still somewhat untested waters of potential patent infringement if the Corps began making AM replacements for patented OEM parts.

In 2017 Marine Officers Zach Daugherty and Andrew Heiple looked at AM solutions for the Marine Corps. Matthew Einhorn examined how operational readiness in the Army could be improved via AM technologies, and David Coyle, a mechanical engineer working for the Naval Supply Systems Command, looked at AM applications for Naval Aviation Systems. All of these theses, though focused on the requirements of different services, examined and updated NPS academic knowledge of current and near-future AM technology and made recommendations for specific commercial systems for potential purchase. The first year that anyone looked specifically at aviation applications internal to the military was 2017; OEMs had already been using AM to produce some of their parts during production for years. Aviation is a more challenging environment for logistics and for AM as the tolerances for parts are often much tighter than those of ground equipment and the risks associated with part failure are likely to be more catastrophic. Also in 2017, the Marine Corps released MARADMIN 594/17, which 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 point of contact, and red items could be AM produced only in, essentially, dire straits or with significant prior approval at very high levels. Also noteworthy in the MARADMIN was paragraph 3.a.2.c that states- "The guidance herein does not apply to Marine Corps tactical aviation."

In 2018, the Marine Corps released MARADMIN 209/18 that provided an interim policy on the use of AM in Marine Aviation. Essentially, this MARADMIN refers approval of AM produced parts to NAVAIR, which has been working on the issue for several years already as pointed out by Coyle.

In summary: at present the Marine Corps owns and operates AM technology at the MEUs, maintenance units, and the depot level for repair parts. NEXLOG and the HQMC AM team are working towards integration of AM into the USMC supply system via the colored bin system worked out in MARADMIN 594/17, and there is a database of digital AM models currently maintained by NEXLOG. Maintainers, at all levels, are now being schooled in AM techniques and applications during their initial and follow-on training. AM is beginning to be used in aviation, and risk measurement and mitigation processes already in place in the Marine Corps are being applied to AM parts for both ground and aviation. However, many questions remain unanswered. NEXLOG will eventually have to move on from AM, as the organization exists to promote the future of Marine Logistics and will not be in charge of AM forever. In fact, NEXLOG is currently focused on a variety of potential future capabilities. The primary points of concern with regards to AM within the Marine Corps when NEXLOG transitions to other projects are: who will take up the mantle of responsibility for AM and should there be a permanently standing unit dedicated to the task?

Whatever organizational construct takes over AM from NEXLOG will face many challenging tasks. The Technical Data Package, the current USMC repository of digital AM designs, is assumed to be secure, but how do mechanics at the using unit level obtain designs they can trust and that are approved for use? If a using mechanic comes up with a slightly better design, how does the Corps evaluate this design and promulgate the best design to the rest of the Corps? Does The Marine Corps currently test AM produced parts via destructive and non-destructive testing in order to compare them with OEM parts? Can the Corps base risk management and mitigation strategies on the outcome of the aforementioned testing? Should Marine Corps contract methodology be amended to include rewards to contractors for designs that are more easily 3D printed organically in the Corps, reducing their future logistics/repair timelines? Should the Marine Corps purchase rights to older designs so that they can legally AM parts for older PEIs?

III. RESEARCH METHODOLOGY

A. SYSTEMS ENGINEERING ANALYSIS

The Systems Engineering method used for this analysis is based on Functions Based Systems Engineering (FBSE). FBSE is an iterative analysis that begins with assessment of the top-level required functions of a given system. After identifying the top-level required functions, the engineer iteratively descends a notional hierarchy of functions until the lowest divisible function is reached. In this case, we begin this analysis with top-level functionality the Marine Corps needs to maintain in the future to support continued use and increased efficacy of AM concepts and techniques. From there each functionality is developed downwards until no more division is possible. This provides both required bottom level functionalities and a rough hierarchy of function ascribed to the system.

B. USMC AM REQUIREMENTS

At present, the NEXLOG AM Cell and the MCSC AMOC provide the following basic functionalities for the Corps: technical expertise in AM, maintenance of the digital AM parts inventory, and the Corps' policy on AM. The MCSC AMOC provides the first two, with the NEXLOG AM Cell providing the policy and being influenced by the MCSC AMOC (MCSC AMOC Brief, 2018). While there are many more things both organizations currently handle with regards to AM, it is these top-level functions from which all others stem. These functions need to be preserved in whatever organization manages AM in the Corps because all three are crucial to the continued performance of the mission of the Marine Corps and require constant input and ownership. Top-level AM functions are depicted in Figure 1.

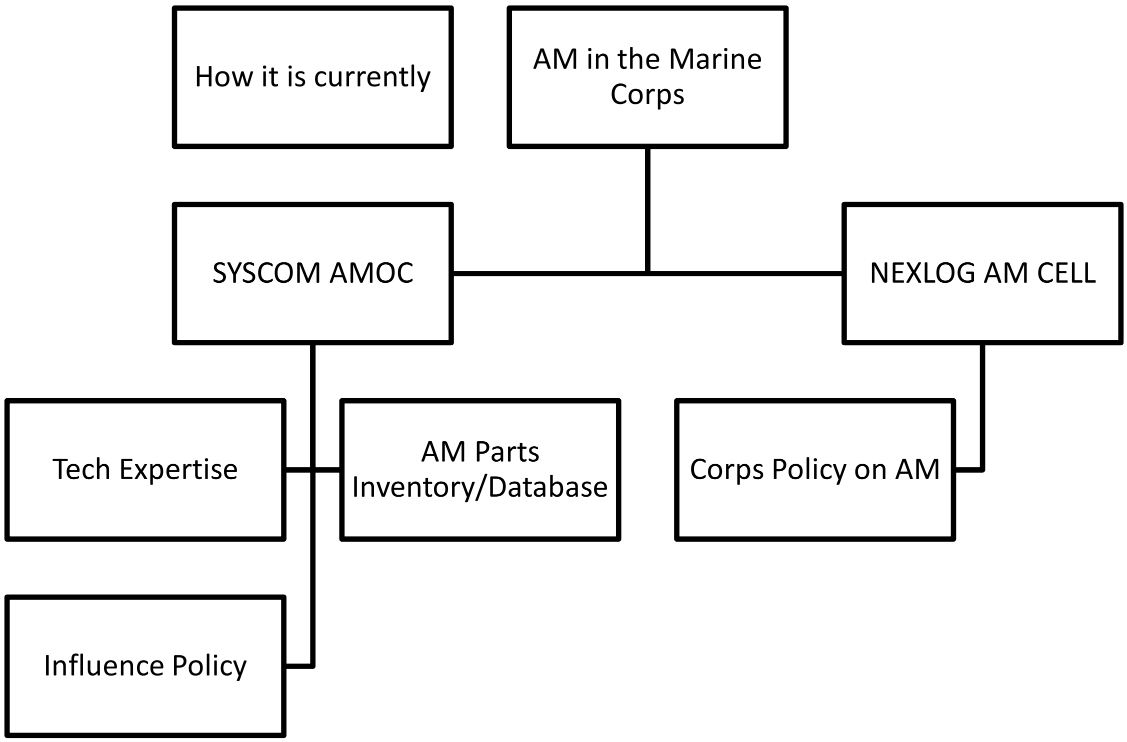

Figure 1. USMC AM Requirements

General Dana, USMC, while serving as Deputy Commandant for Installations and Logistics, expressed a desire to shut down the NEXLOG AM Cell before the end of FY19. With AM in use throughout the Marine Corps, a system in place to organize parts, and policy written, he indicated that it was time to close up this intermediate step of the AM Cell. The MCSC AMOC was briefly under a similar time-line, but that has been walked back in recent months as it has become apparent that MCSC AMOC is value added to the whole Marine Corps. Therefore, the question at hand is whether the standing organization (MCSC AMOC, sans NEXLOG AM Cell) covers all top-level functionalities required for AM in the Marine Corps. One follow-on question is whether the Corps could be doing more, both with AM in the Corps and with AM in general. With an eye on that horizon, a FBSE style analysis was conducted on the functions required to keep abreast of AM developments and ensure the Marine Corps is getting the most output relative to the money and focus invested in this area. It is clear that there needs to be an organizational leader for AM in the Corps, and it seems that the unit in charge of AM for the Marine Corps is going to be the MCSC AMOC for at least the short term. This new AM unit, be it an enhanced MCSC AMOC or an entirely new unit, has to cover all the functionalities previously provided by both the MCSC AMOC and the NEXLOG AM Cell. Its top-level functionalities are depicted in Figure 2.

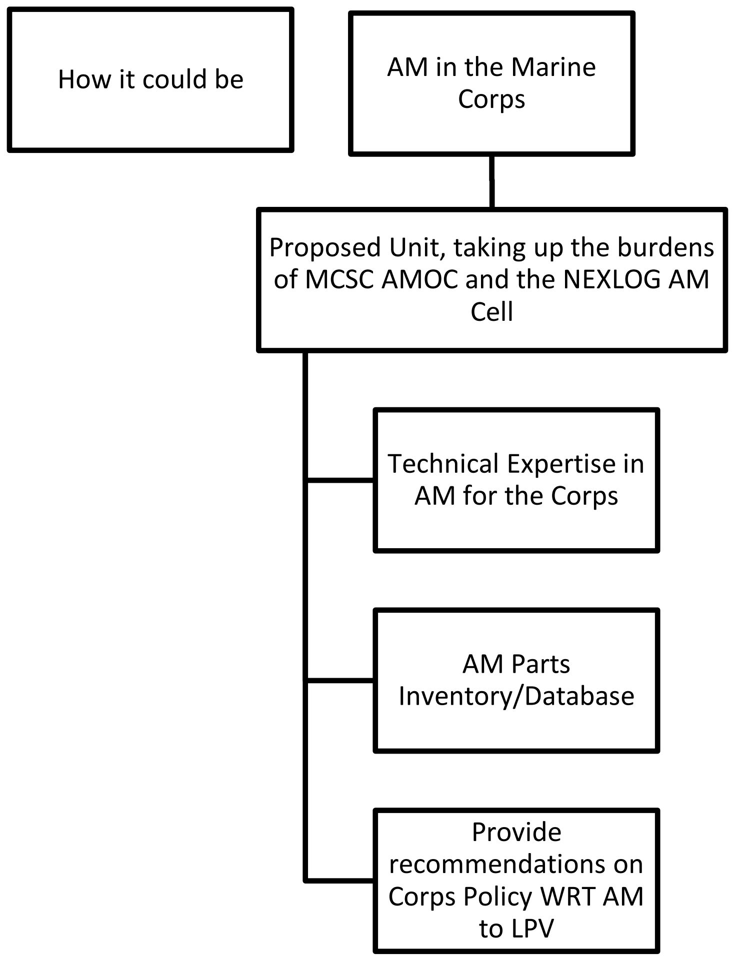

Figure 2. Top-Level AM Functionalities in the USMC

The only change from the MCSC AMOC/NEXLOG AM Cell split is that this proposed unit, unless positioned organizationally directly under the DC I&L Logistics Planning and Vision (LPV), could only provide recommendations on Corps AM policy to LPV. It could not itself be responsible for writing or promulgating policy as that requires at least a Deputy Commandant. Any policy guidance or recommendations from the proposed unit in charge of AM in the Corps, even if it were an enhanced MCSC AMOC, would have to be approved and published by DC I&L, likely after review by LPV.

This new AM unit would be the body of resident technical expertise on AM in the Marine Corps, which in this work has been sub-functionally split into "help to using units" and "help to the Corps" to capture the two main thrusts of organizational expertise that would have to be maintained. The Corps needs to stay abreast of upcoming systems and capabilities, and requires subject matter experts (SMEs) in order to do so. This same proposed unit in charge of AM for the Corps would be responsible for making purchase recommendations as new commercial systems become available because the Corps would want to expand both their capability and their selection of 3D printers available to using units. One area in which the Corps needs to improve is the integration of AM concerns into contracting, especially for PEIs (Acosta, 2018c). This author believes that this proposed unit will have to be tied into the Contracting Officer Course, in order to work AM concerns into major end item contracts from the very beginning. This "help to the Corps" functionality is depicted in Figure 3.

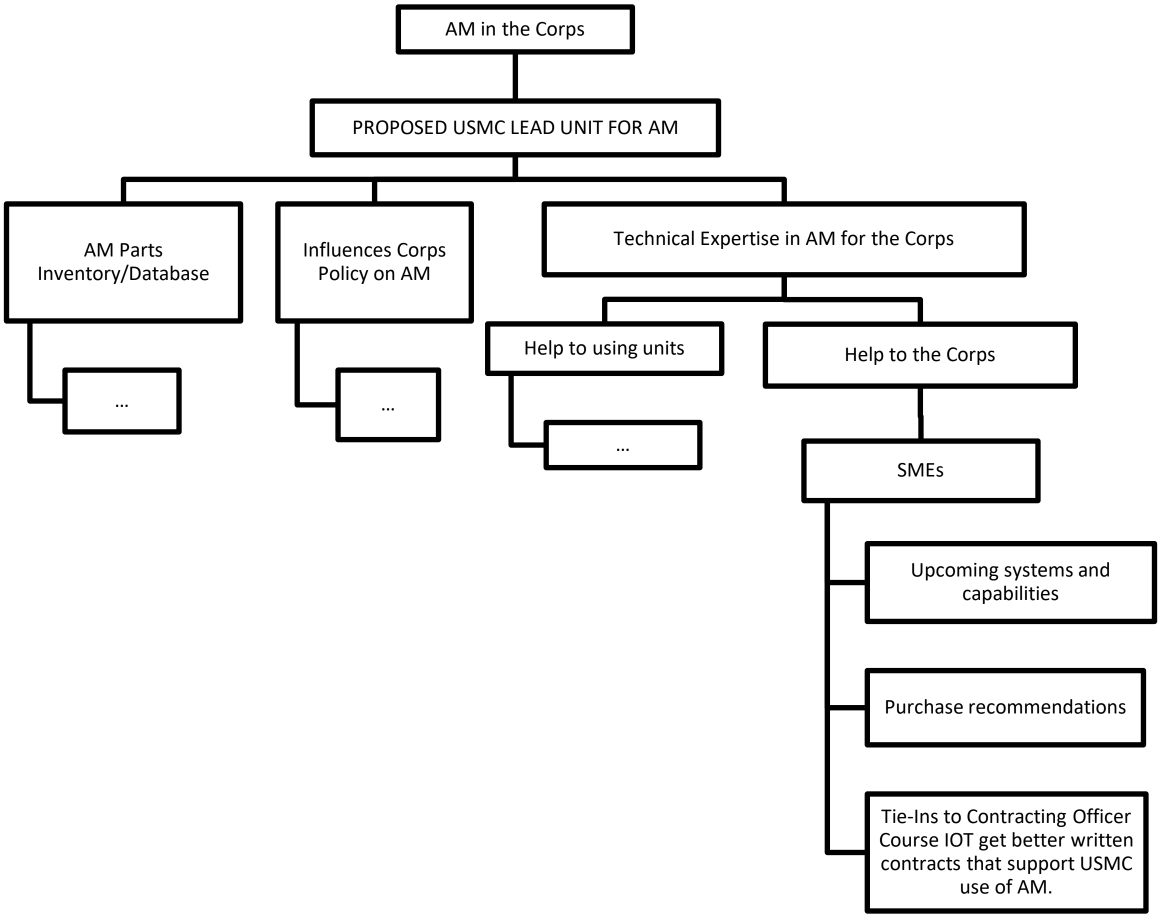

Figure 3. Breakdown of "Help to the Corps" Functionality

The other function under "Technical Expertise in AM for the Marine Corps" is "help to using units." With units down to the company level able to purchase approved 3D printers through the Marine Corps supply system, a body of experts needs to be maintained in order to answer user questions and help them solve problems. "Help to using units" is broken down into three sub-categories of assistance that the proposed unit could lend: Mobile Training Teams (MTTs), Phone Calls, and Deep Reach Back. MTTs are an age-old practice in the Marine Corps wherein an expert unit or organization sends out small teams to run either training courses or "train-the-trainer" courses in order to improve unit efficacy in a given field. The MCSC AMOC already has 3D Printing MTTs available by request. These MTTs go out to units that own 3D printers and run classes and workshops with Marines to help improve their efficacy with 3D printing and other advanced manufacturing techniques (Freedberg, 2018). This MTT capability must be retained in order to maintain a competent cadre of AM users throughout the Corps.

Support phone calls can be considered much like commercial tech support—if equipment is not working at a particular unit, the Corps needs experts that can be reached via phone to help troubleshoot. Usually in the Marine Corps, that sort of assistance would go back up the chain of command. Higher-level units have increased capabilities, especially in technical fields such as communication, and are often able to make more sophisticated changes to Marine Corps systems than low-level users. Because the systems in use are so specialized and the familiarity with them relatively limited amongst Marines, the Corps-wide phone call support capability is crucial. Currently, the MCSC AMOC is providing near-24/7 assistance via phone from qualified engineers who are experts in digital design and 3D printing (MCSC AMOC Brief, 2018). This capability should be both continued and strengthened in order to increase individual unit and Marine utilization of the available assistance and to demonstrate, through results, how powerful a tool AM can be for Marines at all levels.

The last form of important help to using units is the deep reach back capability that the MCSC AMOC currently heads. When MCSC AMOC wants to test a part via destructive or non-destructive testing (D/NDT&E), often in comparison with an OEM part that performs the same function, MCSC AMOC engineers reach out to a wide variety of National Laboratories and National Engineering Resources. The Marine Corps pays for the time and effort spent by these labs, and the labs conduct testing as requested via the MCSC AMOC on a first come first serve basis. If these labs are working on projects of their own, oftentimes testing parts for the Marine Corps is assigned a lower priority. This leads to an important question—should the Marine Corps develop and resource an internal D/NDT&E capability? If the Marine Corps were able to destructively and non-destructively test parts on their own, they could stop their reliance on national laboratory assets and determine their own prioritization. Such an endeavor would admittedly be costly in both manpower and resources. “Help to using units” is depicted in Figure 4.

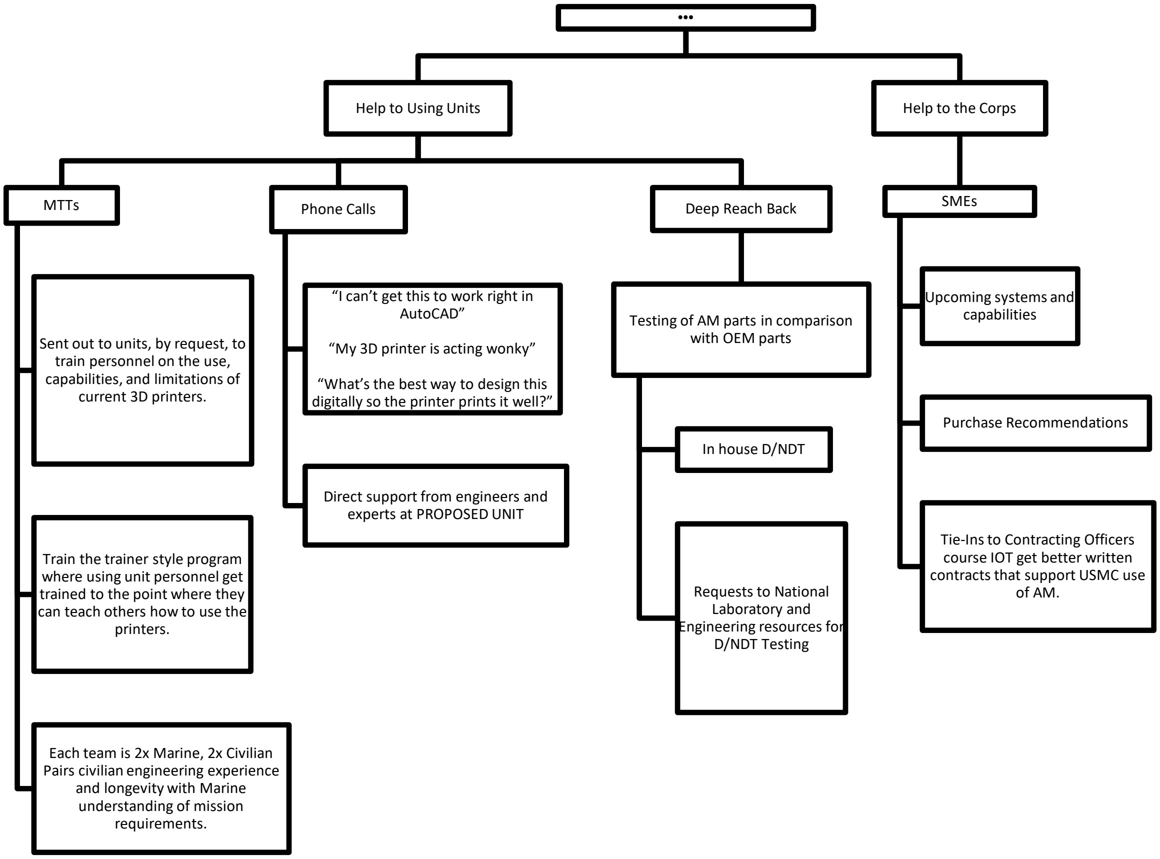

Figure 4. Breakdown of "Help to Using Units" Functionality

The next function that needs to be maintained after the closure of the NEXLOG AM Cell is the AM parts inventory/database (MARADMIN 594/17, 2017). This functionality requires three sub-functions: physical security, access control, and reliability. At present, the USMC is using a lightly secured website hosting a database maintained by the MCSC AMOC. Marines who seek access to AM resources digitally request credentials to the database, and they are approved online. They use their Common Access Card (CAC) to log into the database, which is maintained at the UNCLASSIFIED level. The web user interface (UI) has been described as 'not great' and as having very limited capabilities. The Global Combat Support System – Marine Corps (GCSS-MC), which to date remains incomplete, is essentially a structured query language (SQL) database that was intended to perform many logistics functions and to streamline significant portions of the Corps' supply chain, such as automatic reorder of parts after expenditure in maintenance operations and tracking average lifetimes of various parts with statistics such as MTBF and MTTR. GCSS-MC has never achieved all of the functionality it was intended to have. As of late 2018, GCSS-MC was on version 12, and the contractor building it plans to release version 13 in 2019. The current iteration is not as expeditionary or lightweight as the Corps needs it to be in order to be utilized in remote and austere environments. It is likely that there will be similar issues with the AM parts inventory/database. The authentication system, at present, is mediocre but sufficient for the level of information currently in the database.

However, suppose four different Marines digitally design a replacement switch for a truck and they all upload their designs into the database. Which one is the best? How would the Corps make this determination? How does the Corps ensure that the best design percolates to the top? What if one performs better in certain environments than others? At present, the Corps cannot track that information over time. Version control presents similar issues. The current database does not support classified parts even though there are classified parts that could be printed if a printer was tied to a classified network. This is an administrative limitation (MARADMIN 489/16, 2016). If the printers are connected to classified networks in order to print classified parts, the printer location has to be secured to the same standard as any other location dealing with that level of classification. It would require a separate database on a classified network with additional access controls in place to ensure that only appropriately cleared personnel are accessing these designs and printing them. The system would need to be able to track every time a classified part was printed.

The benefits of supporting use of classified parts would be considerable. The Marine Corps maintains classified spaces throughout its bases and installations, and these spaces are cleared to have connections to classified networks. Sourcing classified parts is a logistical challenge, so printing them in situ would reduce PEI downtime and would increase the speed with which repairs are made. This poses another question for the Marine Corps- do they want to have the capability to print classified parts? If they do, that would require a considerable expenditure of resources and personnel to maintain that capability.

Additionally, reliability is critical functionality that must be considered when discussing the parts database. Access and control are key features in any database, but one from which Marines would be printing potentially mission critical parts would need to have robust authentication and access control. AM parts can be compromised intentionally, but they could also be accidentally compromised by a Marine making an accidental adjustment to a technical data package (TDP), which is the digital design and metadata for a given part. TDPs can be used to print parts via AM. Access and control are a large component of the AM parts inventory/database function. A breakdown of the AM parts inventory/database functionality is depicted in Figure 5.

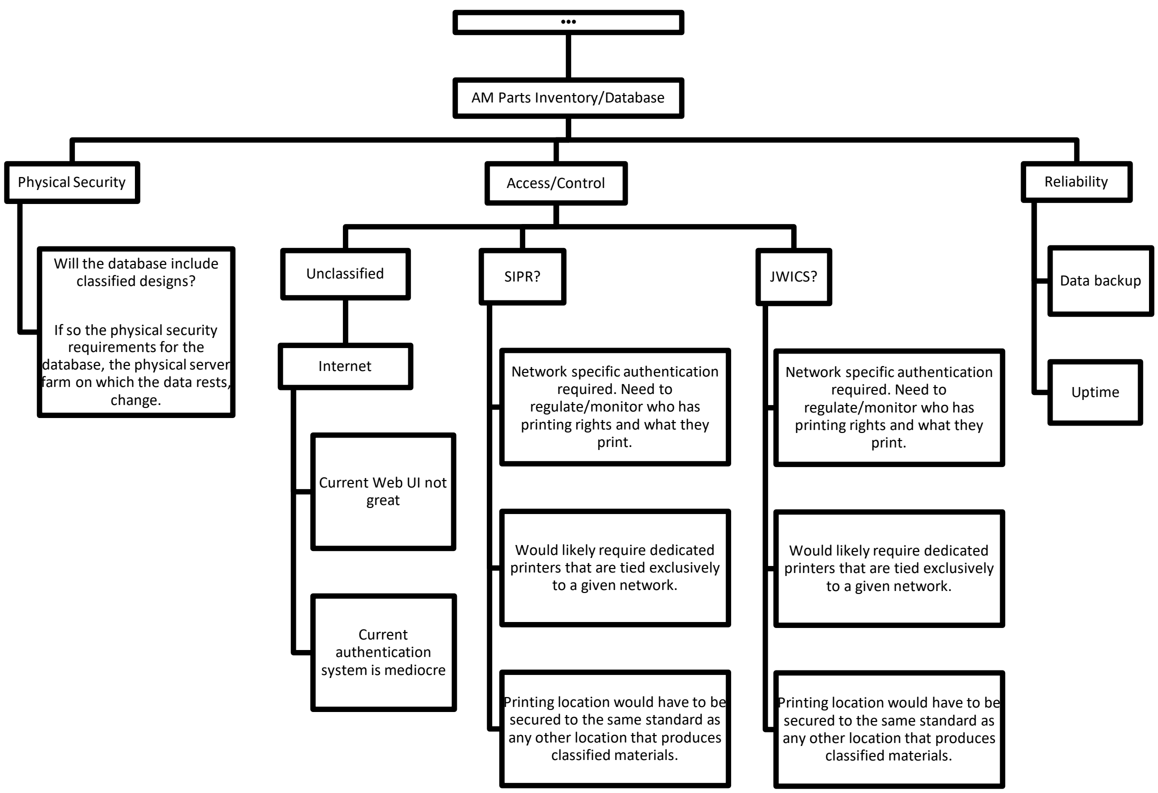

Figure 5. Breakdown of "AM Parts Inventory/Database" Functionality

Lastly, the proposed new AM unit in the Marine Corps would have to provide guidance to LPV for future policy on AM, the legality of printing parts, and advice regarding maintenance/upgrading older policies such as the bin system. The legality issues often get brought up in discussions about AM and have largely been settled (Acosta, 2018a, 2018b, 2018c); however, the Marine Corps should aim to give themselves more leeway in that regard. They need to think about and plan for the use of AM technology in every contract they write, in every statement of support they build, and for every principle end item they field. To that end, it might be beneficial to include a legal representative who can assist with a brief training period at the Contracting Officer Course. Subordinate functions of the current policy include risk management and continuing the discussions over the need/desire to, and inherent risk in, printing parts for aviation applications. The debate as to whether or not the Corps should print classified parts carries important elements of the risk management that would be addressed by this unit. At the end of the day, this proposed unit will need to be able to advise the DC I&L on policy recommendations and the path forward for the Marine Corps and AM. The "Influence on Corps Policy on AM" functionality is depicted in Figure 6.

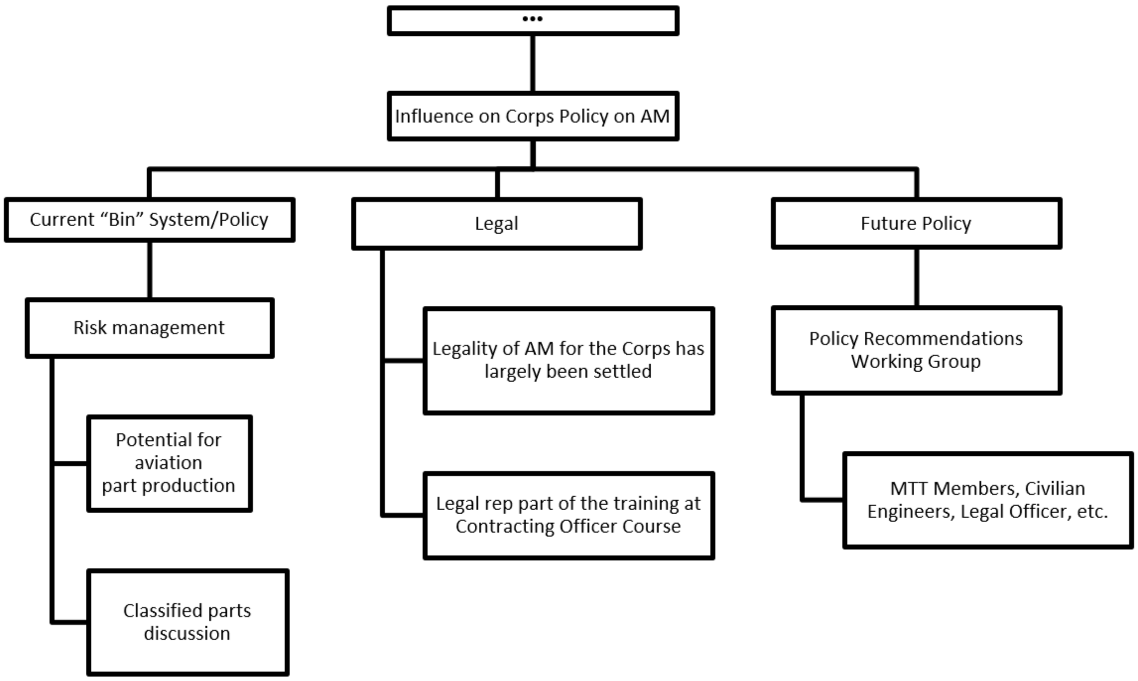

Figure 6. Breakdown of "Influence on Corps Policy on AM" Functionality

The top-level functionalities down to the detailed specific functionalities for the proposed new Marine Corps AM cell are depicted in Figure 7.

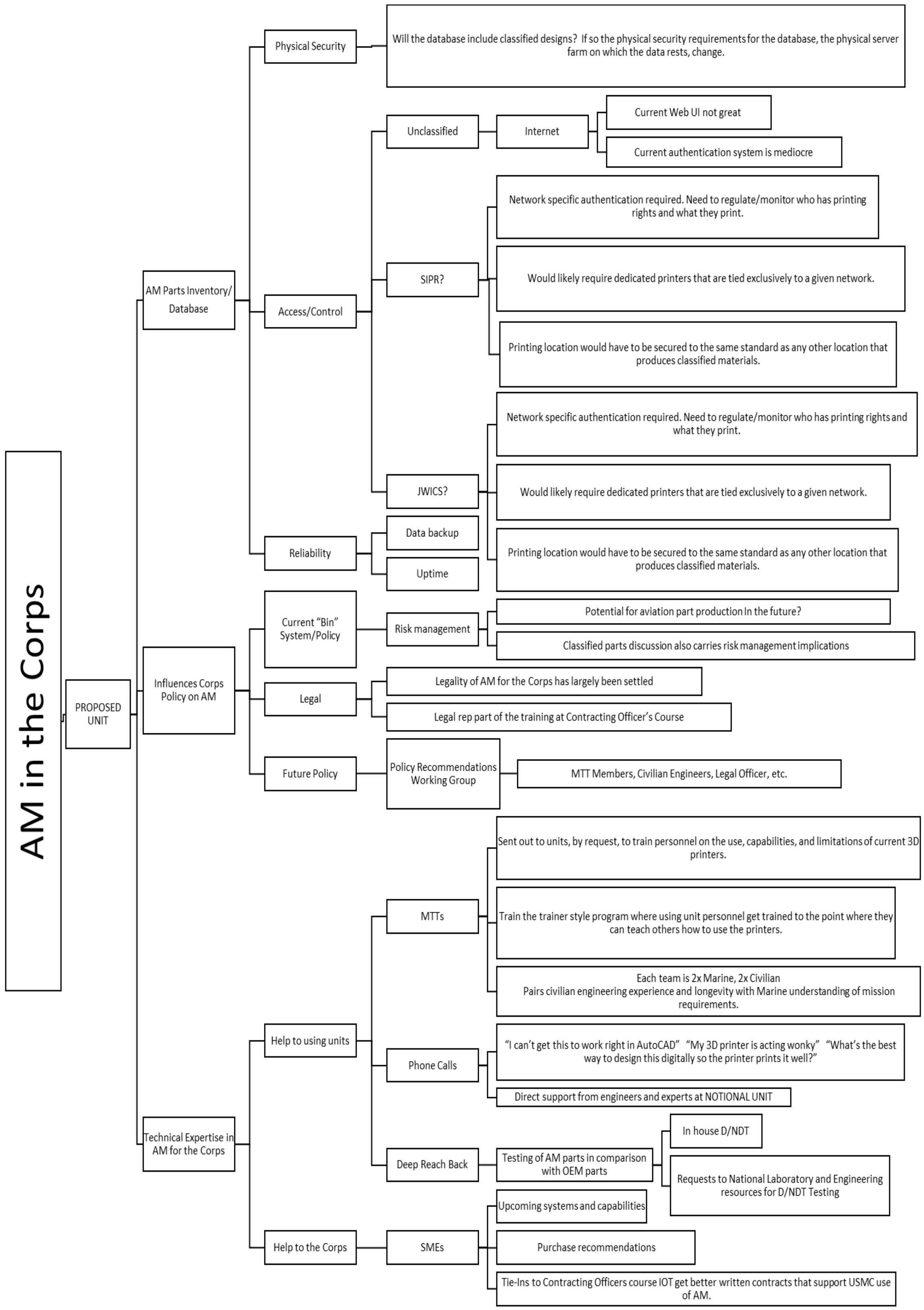

Figure 7. Complete Functions Breakdown of AM in the Corps

Of the functionalities required to support Additive Manufacturing in the Marine Corps, those the Corps currently possess are highlighted in green in Figure 8, and capabilities they only partially possess highlighted in yellow.

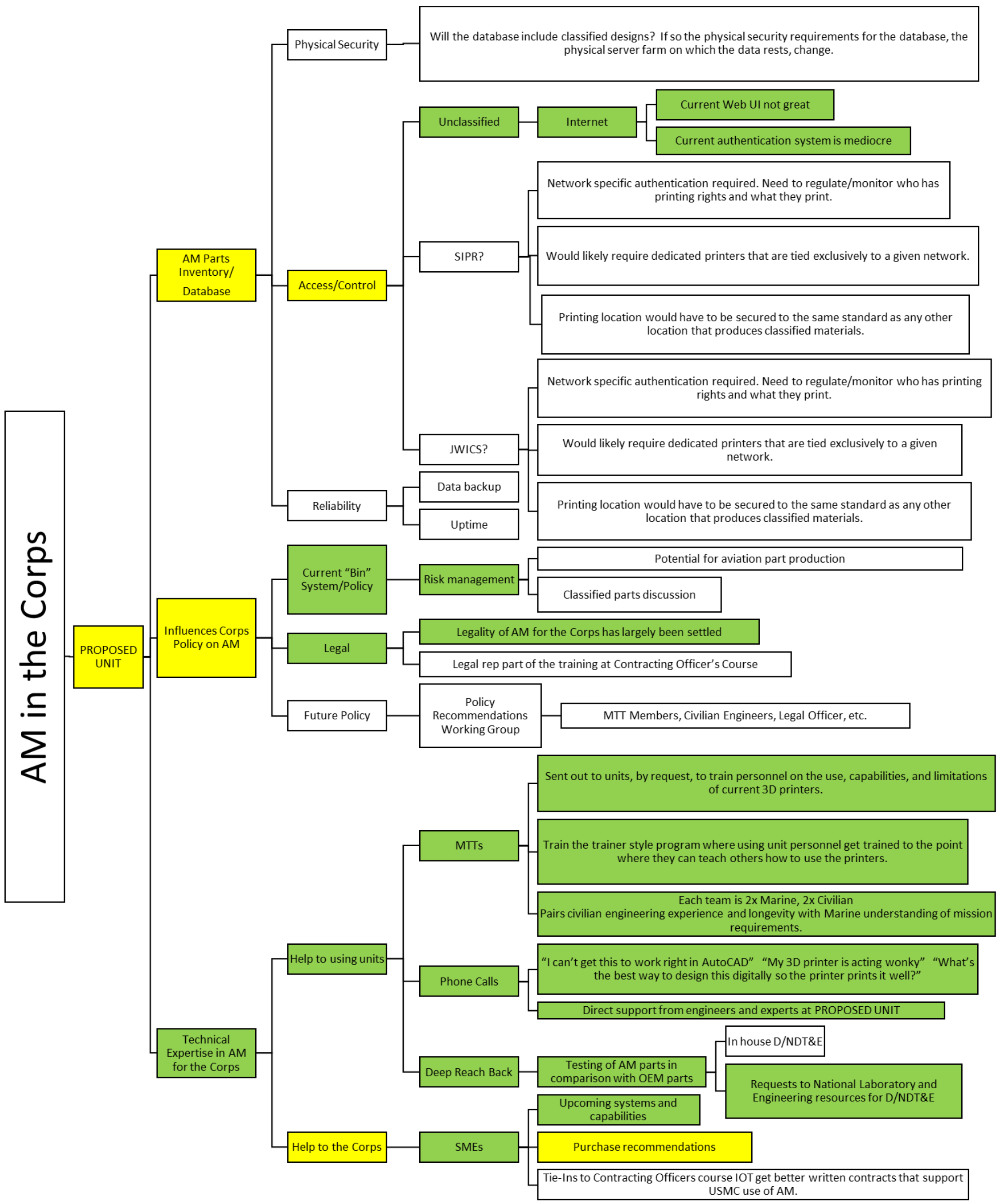

Figure 8. Current USMC AM Capabilities, Highlighted in Green

Between the MCSC AMOC and the NEXLOG AM Cell, a good portion of AM requisite functionalities are currently covered. What is the Marine Corps missing? In Figure 9, the author has highlighted in red additional capabilities and functionalities the Corps could expand to have. The author has highlighted in yellow those areas in which the Corps is already working but could improve by adding or enhancing sub-functionalities.

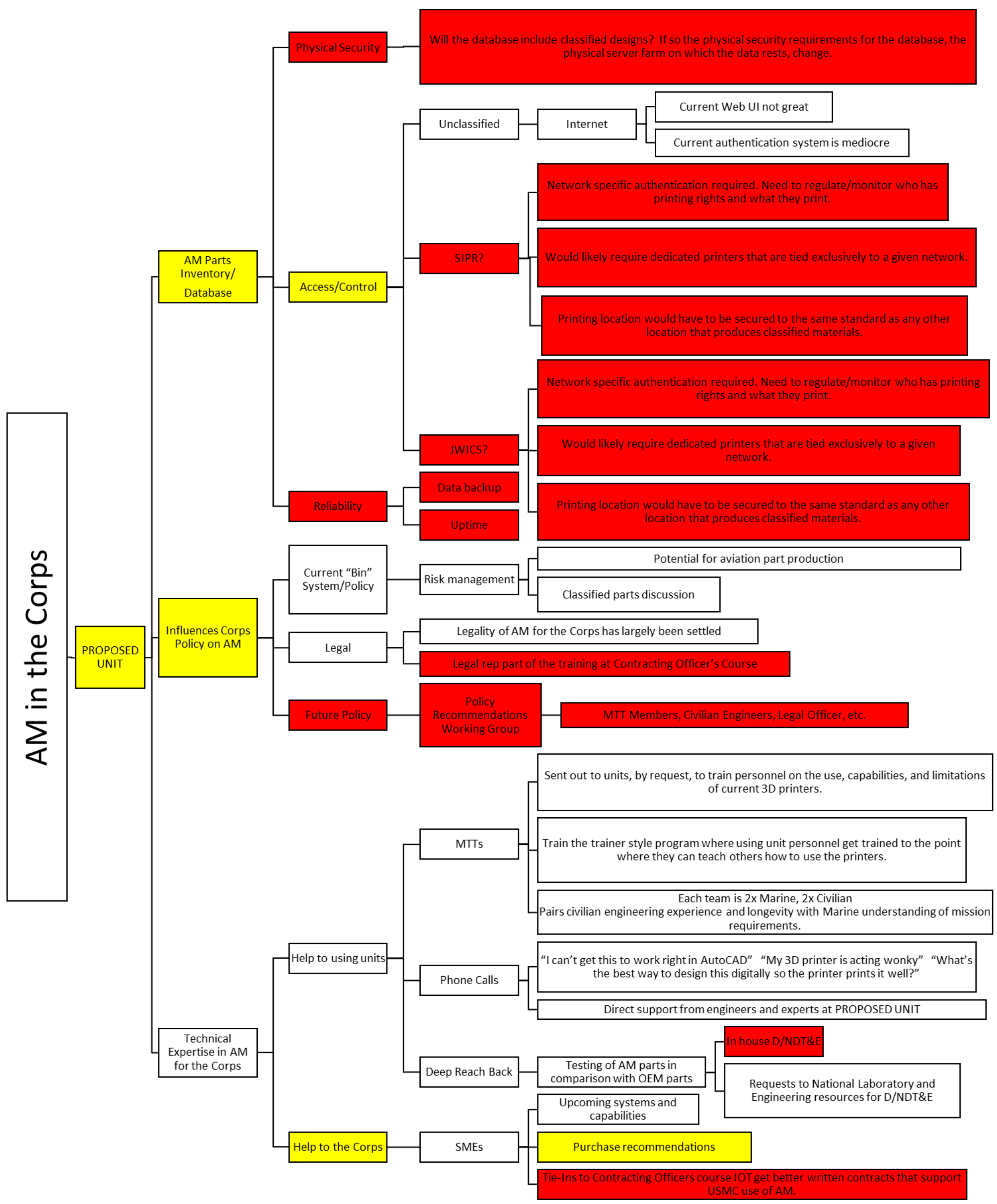

Figure 9. AM Capabilities not Currently Present in Corps Structure, in Red

When comparing these two diagrams, it is easy to see that the Corps have focused the most effort and resources on support to the using units—which is good. However, several systemic issues exist that are holding back the potentially amazing aspects and capabilities inherent in 3D printing. As previously mentioned, the current database system is neither robust nor highly usable. It could stand to be improved in terms of access control and Web UI. There is a contractor currently running the database, but if the Corps want to be able to print classified items, they will need to take over the database in full, internal to the Marine Corps, or at a minimum have a version or versions of it resident on higher classification enterprise networks such as SIPR or JWICS. With both those possibilities come necessary increases to the physical and digital security of the repository itself. The author would argue that having a contractor running the database, even the unclassified one that exists currently, is opening the Corps up to risk from enemy actions. For example, if a foreign agent got access to the system as is and was able to post a seemingly legitimate part for a 7-ton Medium Tactical Vehicle Replacement (MTVR) where the part would quickly break or might be vulnerable to cold weather, the entire vehicle might become unusable in cold weather. Complete Marine Corps ownership of parts is the safest available option. A joint DoD database might work as long as it, even for the unclassified parts database, met FOUO security standards and controls and the Corps increased the level of scrutiny it has at the enterprise level over what individual users are doing. If a user wanted to be able to print classified parts, that might require a commensurate increase in physical and digital security, tying particular printers to the classified network and requiring strict scrutiny not just on who is printing what, but how many they are printing and what they are being used for. It is conceivable that use of a blockchain style ledger system would be handy here, but that is beyond the scope of this effort.

Another issue the Corps is addressing but has yet to resolve is the ability/willingness to produce aviation parts via AM (MARADMIN 209/18, 2018). Marine Corps aviation has the most stringent requirements for low MTBF and consistent MTTR, and a high equipment failure rate, some of which have let to Class A mishaps. If Marines can trust parts manufactured via AM they can make more aircraft operational and can keep more aircraft operational. The concern, in short, is risk management. It is a twofold problem: A) How does a staff officer get a number, a percentage, or other concrete value that tells them how much more or less likely this part is to fail if it is produced via AM compared to the same OEM part and, B) How might this officer portray that percentage, that number, that data (essentially their reliability estimate) to a commander in a way that will enable him or her to make appropriate risk and mission-based decisions? For example, say a unit is planning a rapid response NEO (non-combatant evacuation operation) attempting to extract Americans from a country in which the political situation is rapidly degrading and that will likely become life-threatening for Americans in the near future. If the nearest MEU only has three out of five of their helicopters functioning, that is going to severely impact the speed with which they might infiltrate security personnel and ex-filtrate non-combatants. Maybe at the onset, the MEU commander might be unwilling to replace a faulty part on the two down helicopters with a 3D printed one if it is a critical flight systems part, the failure of which might immediately make an aircraft go down. As the crisis deepens, this commander might be more willing to make that replacement in order to get those two birds up. He might consider that having two additional rotary wing assets might make the difference between successful evacuation of all non-combatants and his personnel and having someone still in the embassy when a riotous crowd might break down the doors. How can a staff officer paint the risk picture for the commander? What factors change the efficacy or reliability of a 3D part? In some scenarios, it might be perfectly acceptable if an AM part is understood to have a consistent but lower MTBF compared to the OEM part. It might make sense to use the AM part, replacing it more often. While this would mean more part replacement, it would still serve to shorten the supply chain by producing the part via AM in situ. It could also mean mission accomplishment instead of mission failure, even if the part is known to not last as long as its OEM version.

What decision makers need to have is data—data which can only be obtained by conducting D/NDT&E of parts in comparison with their OEM counterparts. At present, MCSC AMOC is the source for that deep reach back to National Laboratories and Engineering facilities. However, the Marine Corps does not, at present, have the facilities, equipment, or personnel to do this testing. The Corps continues to pay national laboratory assets to do the testing when the labs have availability to do so. If the Corps had their own internal D/NDT&E capability, they could prioritize as they see fit and have the data on hand to paint that risk picture for the commanding officer. At present, the Marine Corps is using a RYG coloring system describing notional "bins" that different part types fit into and which have different rules for production and use. Basic rules for each bin are shown in Figure 10.

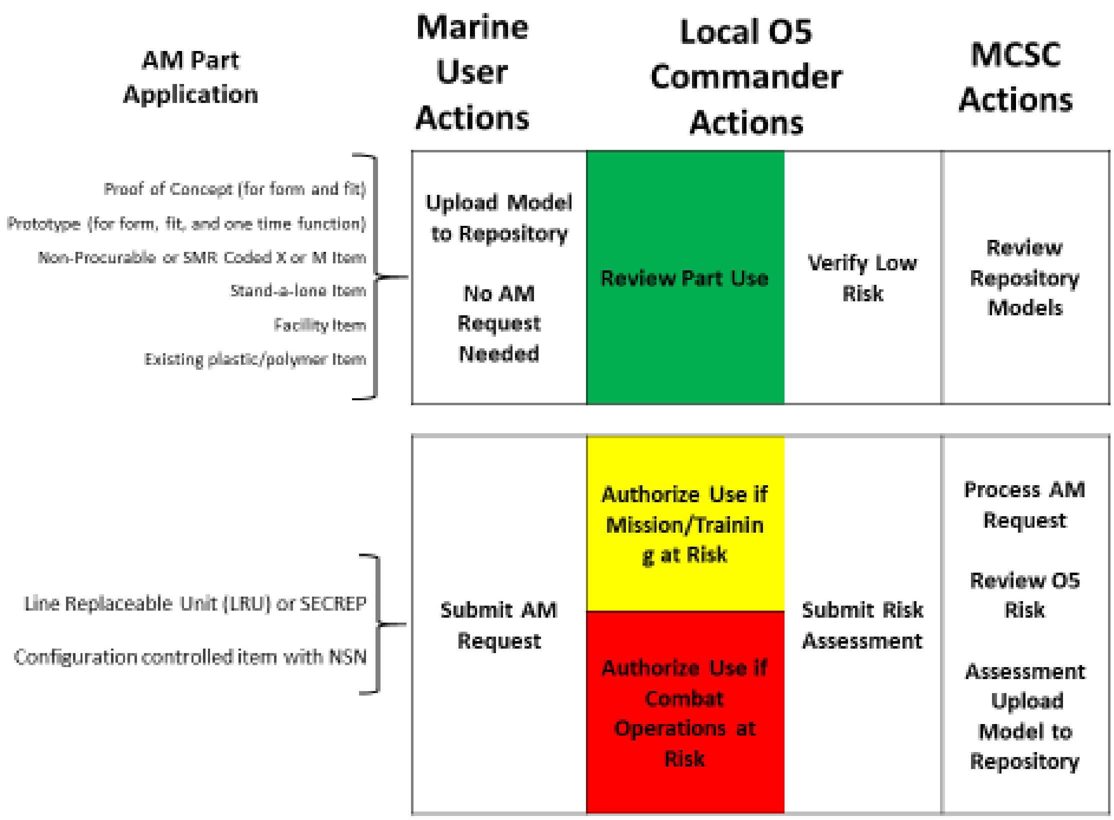

Figure 10. Current RYG Bin System. Source: Acosta (2018)

The last significant difference between the full functionality suite the author has proposed for AM in the Corps and what the Corps currently possess/are using is increased tie-ins to the contracting side of things. The bottom line is that the Corps has largely solved the legality problems with 3D printing replacement parts to replace OEM parts (Acosta, 2018c). There have been many legal challenges to AM parts: 1) Since the OEM owns the rights to the original part designs, can the Corps just copy parts and use them? 2) Is it okay if the Corps makes a copy in a pinch but most of the rest of the time the Corps utilizes standard supply chaining to purchase replacements from the OEM? 3) If a part is no longer manufactured by the supplier, resulting in a situation in which either the Corps would have to make it themselves at the depot level or pay a contractor to produce it for them when they need one (sometimes spinning back up mothballed machinery or factories to do so), can 3D printing help them with that problem set? 4) Can the Corps replace a system or series of individual parts with one manufactured whole cloth via AM because of the unique capabilities inherent in 3D printing? 5) If the Corps replaces an OEM part with a 3D printed one, does that void the warranty on the PEI? Routes to legally producing parts to replace OEM parts are outlines in Figure 11.

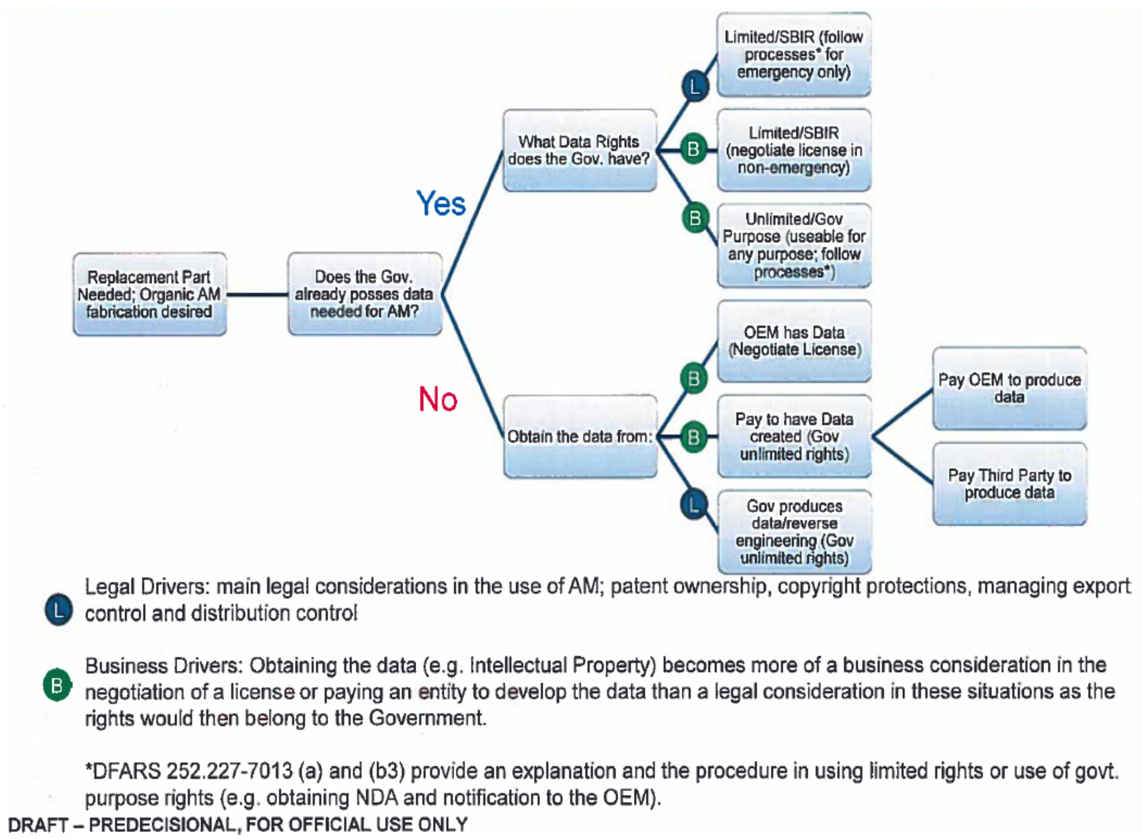

Figure 11. Draft Decision-Making Framework for Part Fabrication.
Source: Acosta (2018b).

6. What if, after the warranty has been voided, the Corps later breaks a piece of the PEI that they cannot reproduce on their own, is the OEM likely to provide service? The answer without delving into legalese is that when necessary they can print anything they need to. Yes, sometimes doing so and replacing an OEM part with one they have printed can/does void the warranty on the PEI. Yes, sometimes, depending on the support contract with the OEM, they can refuse to service the equipment later because the warranty has been voided. If the Corps recreates an OEM part by either hand or "clean" reverse engineering effort, i.e., reverse engineer the part with no prior knowledge, on the part of the organization or engineer doing the reverse engineering of the technical data from the OEM, legally, they are fine. If, however, they use the OEM TDP and print it themselves, they might find themselves in violation of copyright.

What this means, functionally, is that the Corps needs to improve the ways in which it constructs and executes contracts for every piece of equipment the Marine Corps uses in order to support its own ability to decrease MTTR via supply chain shortening by in situ AM. To that end, this research suggests that having a legal representative at the proposed unit in charge of AM for the Corps, or at least available to the unit as needed, is a must. Historically, the Corps has had a civilian legal officer on loan from higher in MCSC who has worked closely with the MCSC AMOC (Acosta, 2018b) as they have run up against these issues. Furthermore, having a legal professional versed in copyright law, contracting, and 3D printing capabilities teach a segment at the Contracting Officer Course and schools that produce USMC, DoD, and U.S. Government Project Managers would greatly aid the adoption of AM by the Marine Corps. On the high end of effort and resource expenditure, adding a step to the contracting process in which support proposals are reviewed by the Organization in Charge of AM for the Corps before approval is advisable. The Marine Corps will continue to be hampered in their efforts to expand their use of AM if they do not begin to write smarter contracts in which they negotiate for whole or partial ownership of TDPs for each and every part. Legal and illegal paths to TDP production from an OEM part are shown in Figure 12.

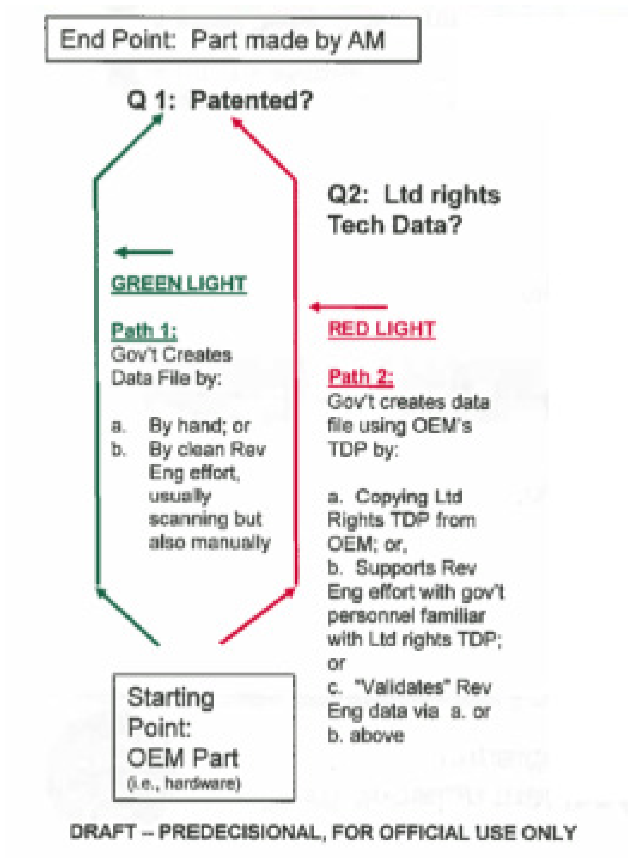

Figure 12. Draft Right and Wrong Paths to USMC TDP Creation from OEM Part. Source: Acosta (2018a)

The Corps needs to have written agreements, before push comes to shove, indicating when and in what circumstances it is allowed to print its own replacement parts and when it should refrain from doing so in order to best utilize the support contract from the OEM. The Corps will need decisions about all of this—from Corps-wide policies on support/maintenance/supply contracts down to detailed instructions for the using unit level regarding what they can and cannot do in order to keep those unit commanders out of legal hot water.

C. OTHER SERVICE SOLUTIONS

Both the U.S. Air Force and the U.S. Army have designated lead units for AM in their structure. The U.S. Army has the Center for Excellence for Advanced and Additive Manufacturing at Rock Island Arsenal (IW Staff, 2019). The U.S. Air Force has designated their longstanding AFRL Materials and Manufacturing Directorate (RX) as the Air Force lead for AM. The RX directorate at AFRL is based at Wright-Patterson Air Force Base in Ohio. The AFRL is a subordinate command of the service's major command Air Force Materiel Command. It is easy to draw a line directly from the highest leadership in the Air Force directly to their designated lead unit in AM. RX Directorate reports to AFRL, which reports to Materiel Command, which reports directly to USAF HQ.

On the Army side, "Rock Island Arsenal has been producing readiness for our Army … since 1862" (IW Staff, 2019). The Center of Excellence was provided with $20 million in funding and "will serve as a central location to develop best practices and promote execution of the campaign plan throughout the Army materiel enterprise" (IW Staff, 2019). The Center of Excellence is a subordinate element of the Rock Island Arsenal – Joint Manufacturing and Technology Center (RIA-JMTC). In terms of Army structure, the Center for Excellence in Advanced and Additive Manufacturing reports to the RIA-JMTC, which reports to the U.S. Army Materiel Command that is one of the major Army commands. The U.S. Army Materiel command is equivalent to MCSC. The Air Force Materiel Command is similarly equivalent to MCSC. In light of the significantly larger structure, having the lead unit for AM in a given service be two steps down from their respective Materiel command seems like an effective location, structure-wise. The reporting chain to make DOTMLPF changes to the service is short and the supervision over the activities of the AM lead makes sense given the deep ties into maintenance, logistics, and major systems design and manufacture. In contrast, the MCSC AMOC is a fluid team structurally located under MCSC G-3 Current Operations (MCSC AMOC Brief, 2018). Technically that is the same number of structural steps to get to HQ USMC as for the other services. The main difference lies in the designation as lead unit for AM for the respective service and the permanence of the associated structure. The Corps has not yet solidified the AMOC's role or structure. In addition the RIA-JMTC possess internal D/NDT&E capability, which the AM Center for Excellence can leverage without having to go to external labs and resources.

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IV. RESULTS

A. ANSWERS TO QUESTIONS

1. How does the Marine Corps currently utilize AM as a part of its logistics operations?

The Marine Corps is currently utilizing AM technology approximately half as well as it could be. AM is still an emerging technology and the Corps has invested rapidly in fielding the technology very early on. They are not at true just-in-time (JIT) manufacturing yet, but they are much closer than they were a few years ago. Five years ago, they did not have a single 3D printer in the Corps and now they cannot track them all. AM utilization exists at all levels responsible for maintenance and resupply, from individual companies to the depot level. Maintainers are beginning to think about AM as a quick and effective way to produce replacement parts and systems. The MTTs from MCSC AMOC are enhancing individual unit abilities in 3D printing and creative design. The RYG bin system that is in place is sufficient to provide guidance on part fabrication. Guidance exists on reverse engineering. GCSS-MC does not yet take AM into account, nor does it track efficacy of AM parts in the field (however it does not track that for OEM parts either). Contracting officers and program managers are beginning to take AM into account. Comparing what the Marine Corps is currently doing with AM to what it could do, as outlined via a system of systems analysis above, one could say the Marine Corps is doing about 50% of what it could be doing with AM. The Corps has not made, in policy planning or execution, a mistake; they just have not yet been able to fully utilize the possibilities of AM technology.

2. How might the Marine Corps organize itself to enable it to optimize use of AM to enhance warfighting efficiency?

The first part of this question involves ensuring the Corps has the latest equipment and capabilities while not wasting resources on every incrementally improved printer that hits the market. It is a question of ongoing research and analysis. As 3D printing capabilities grow and improve, the Corps will need to continually reassess if the printers they possess are good enough and whether upgrading to newer and better printers is worth the capital and manpower outlay to buy, train on, and use them. For instance, an increasing number of materials can be used as 3D printing mediums, and that trend will continue. Materials continue to be developed specifically because of ease of use in 3D printing useful objects. Therefore, the proposed unit in charge of AM for the Corps will be required to assess industry progress and conduct cost benefit analysis to determine decision points and timelines on which the Corps will invest in cutting-edge equipment.

Similarly, the accuracy of 3D printing continues to improve, with printers capable of accuracy down to ten microns already available on the civilian market. The initial 3D printers purchased by the Marine Corps were not nearly as accurate. However, purchasing new systems every time a new capability comes along is wasteful. One of the required abilities in an organization dedicated to leading 3D printing in the Marine Corps is that it can dedicate experts, likely civilians (not transitory active duty personnel) to understanding the capabilities of the new systems being produced. These engineers can also conduct analysis to determine where the tipping points are—i.e., when do the technological advances make enough of a difference in capability for the Corps that it is time to upgrade?

An additional concern is whether large structure change is required to meet the needs of the proposed AM lead organization. This analysis suggests that only minor structural change needs to be made to the Corps—mostly within MCSC, to take nearly full advantage of AM. However, if the Corps decides to go with the "Heavy" Course of Action (COA), detailed later in this work, significant increases in the number of civilian scientists and engineers employed by the lead AM unit would be required.

Another area of concern is the digital repository of TDPs. The current database, while useable, does not meet the Marine Corps' future needs. Currently, the Corps contracts out the database to Innovate Defense, a defense contractor. They provide, maintain, and modify the mm.md5.net database (the Marine Maker Community Database). Right now, authentication is easy, and consequently access is not tightly controlled. The database is accessed from the open internet, so it has no ability to store classified designs of any sort. Without delving into a network security or information warfare discussion, it is the opinion of this author that an open-internet based repository of TDPs for USMC parts (even though they are unclassified parts) poses security and other risks. It is the opinion of the author that the Corps itself should maintain and secure their TDP repository and more tightly control authentication, access, and track how much, and what, any given user is printing.

Yet another, and perhaps the most important, question is whether the Marine Corps should invest in the business of comparison of AM parts with OEM parts in order to develop risk comparison and mitigation strategies for commanding officers to balance against mission accomplishment and unit readiness, and if so, how? As shown in the previous chapter, they rely on national laboratory assets for deep reach-back, especially in support of D/NDT&E comparison of 3D printed parts to their OEM counterparts. The Corps recently started printing impellors for their main battle tanks, a crucial component that undergoes a lot of stress and that is prone to failure. D/NDT&E has shown the printed impellors do not have a failure rate higher than their OEM counterparts, nor do they cause any other negative impacts to the overall system, thus the risk of using them, compared to the risk inherent in using the OEM parts, is minimal. MCSC AMOC came to this conclusion by paying a national laboratory to do the testing and evaluation for the Corps. Therefore, one could say MCSC AMOC is in the business of comparing AM and OEM parts to develop risk comparison and mitigation strategies. They are just not doing it internally. In the Heavy COA outlined later, the proposed lead AM unit would develop their own internal D/NDT&E capability as the U.S. Army has done at their Center of Excellence in Advanced and Additive Manufacturing at RIA-JMTC.

Over the long term, the Marine Corps is going to have to modify and then codify contracting methodology in order to ensure they utilize and plan for AM capabilities for every piece of equipment Marines are issued or use. Through this research it has become clear that one of the things that both needs to change the most and yet will be most difficult to change, is the way the Marine Corps designs and procures PEIs. Project Managers remain largely unaware of the capabilities of AM and no specific effort has been made to build AM into the process for design, prototyping, and manufacture of new equipment. It is clear that the Marine Corps should build AM into their contracting system in ways that reward companies that support the following: 1: Make it easier for the Corps to repair their equipment in the field, even without the assistance of trained technicians from the company that made the gear. Equipment, especially new items developed during the OIF and OEF era, often have service contracts that require contact teams from the manufacturer to by physically present to work on equipment, dramatically limiting the expeditionary nature of the Corps and tying them deeply to the manufacturers; 2) Increased use of AM in the manufacture of PEIs; 3) Provision of TDP for parts to the Corps as part of the original contract. The Marine Corps could even have it explicitly stated in the contract that most of the time they will buy replacement parts from the manufacturer, but in cases where the equipment is mission essential and the supply chain too slow to get their part from CONUS to deployed forces in a timely manner, the Corps will produce the part via AM on their own. While such contractual language would have many specific provisions within it, that is for project managers and contracting officers address and is outside the scope of this work; 4) Make the rights to TDPs available to the Marine Corps for purchase as part of the contract. The Marine Corps should buy the appropriate rights to parts that have proven to be amenable to AM so that they can print them, as they need to, when they need to, without any additional legal considerations.

It is recommended that the Corps reward contractors who enhance their ability to use AM techniques to cut down on MTTR, increase MTBF, shorten supply chains, and overall make their equipment more expeditionary. The specifics of how they build that into legally binding written contracts for major PEI programs is beyond the scope of this effort.

A final question regarding structure and optimization is whether the USMC supply system requires modification in order to embed AM from the highest to lowest levels and take greatest advantage of this technology; in short- yes. GCSS-MC has yet to achieve all the capabilities that were planned. Theoretically, it was supposed to do “pull” logistics for the Corps, ordering new parts for pre-expended bins (PEBs) the moment a part was used during a repair. Theoretically, it was going to track breakage rates amongst the entire inventory of USMC parts over several factors like engine time, weather conditions, terrain, using unit, etc. An example of this last capability would be GCSS-MC noticing that whenever HMMWVs that were stationed on Okinawa went to CATC Fuji during the winter, hydraulic lines froze and popped, requiring replacement. That is a climate-driven failure that is predictable, if one knows that the rubber of the lines is essentially conditioned to the warm moist weather of Okinawa, and a rapid change to the cold drier climate of

CATC Fuji causes the lines to break. Experienced hands at Truck Company knew it was likely to happen, and the maintenance Marines in the company brought along extra hoses for their training exercises at CATC Fuji, but that knowledge is not resident in every unit. GCSS-MC, when fully realized, is supposed to track and give users this type of information. AM does not really add any additional complication to the system besides providing another method by which some parts may be produced. The system would have to take into account the possibility of production via AM (including the location of 3D printers) and also be able to source the AM printing material, but those are relatively minor additions. A larger and more complicated change will be the necessity of tracking which TDP was used to print a particular part—they are going to need to track MTBF for each *version* of a specific part, because there may be multiple designs in the AM database for a given part. Theoretically, over time they might find out that a particular TDP is the best one for a specific part—the system should then recommend that design to any mechanic looking to print that part in the future. Perhaps different digital designs work best in different environments. This information needs to be tracked and labeled as such in the database, so that a unit in the Middle East does not print the "cold weather" version of a given part, unless they are driving into the mountains of Afghanistan. These capabilities are already present in the full GCSS-MC plan, they just need to be implemented to get GCSS-MC to where it is intended it to be.

B. DOTMLPF ANALYSIS

No matter which COA the Marine Corps decides to pursue, it is clear that changes will be required in almost every element of DOTMLPF to enhance the Corps existing use of AM and to propel them into the future.

1. Doctrine

Doctrinally, Marines at all levels need to be thinking about what can be done with 3D printing. The "fab labs" and "maker studios" are helping with this effort by generating out of the box thinking and design work from Marines of all specialties. As AM becomes more ubiquitous in society, more Marines will carry working knowledge of 3D printing into the Corps as young recruits, as nearly all Marines do these days with computer systems. Additionally, AM should be considered first among all production methods as long as D/NDT&E shows the AM part to consistently have quality comparable to or exceeding that of OEM parts. Considering AM first, particularly for production of replacement parts, can and will shorten Marine Corps supply chains and decrease the burden on the Marine Corps, DoN, and DoD logistical networks.

2. Organization

Organizationally, the Corps needs the proposed unit to exist and to be the Marine Corps experts in AM, available to assist any unit with problems and projects. This organization needs to be able to influence policy in the Marine Corps in order to drive the way forward with AM. All other units need to be informed about the lead AM unit and to be directed towards them for assistance with design and AM problems. The proposed unit needs to be permanently staffed and made part of MCSC permanent structure.

3. Training

In terms of training, AM training should be added to the military occupational specialties (MOS) schools for maintainers, supply Marines, logisticians, maintenance officers, and comptrollers. Maintainers, logisticians, and maintenance officers will likely need a more in depth education on the capabilities and potential uses for AM, which will have to evolve as capabilities increase. Those Marines will most likely be the ones designing solutions to problems, replacing entire systems of parts with single AM produced parts, and working to improve Marine Corps equipment. Supply Marines, their officers, and comptrollers will need to have a basic understanding of the capabilities of AM so they can work to source both feed stock for the printers and work to increase the use of AM for in situ manufacture of parts that otherwise would require stateside manufacture and an entire logistical network to move the parts to the requesting unit.

4. Materiel

Any service using AM for in situ manufacture of any items are going to need to begin providing, not via COTS, but via their own supply system, feedstock for 3D printers to using units as required for that unit to keep making equipment and parts as needed. Data should be gathered on the efficacy of recycling used/broken AM parts into the raw material needed to print new parts. For more delicate applications, such as metal printing of precision fittings, the quality of the feedstock will need to be carefully monitored to ensure that printed parts meet quality guidelines and parts tolerances/specifications.

5. Leadership

Leadership should be given an overview brief on the legality of 3D printing, the risks inherent therein and how to interpret those risks, and left and right lateral limits on what they can and cannot do with 3D printing. This should be driven mostly by policy which is signed and promulgated by DC I&L. It is likely that commanders of units with internal maintenance capabilities will become well-versed in AM capabilities, but eventually every commander will need to know what they can and cannot do with 3D printing.

6. Personnel

There will not be many changes to Personnel for the Marine Corps to continue implementing AM techniques. The Marine Corps already has maintenance Marines specializing in particular platforms. As experts in the systems they work on and repair, these Marines will be the front line for designing AM parts for each PEI as appropriate. These same MOSs carry with them the resident knowledge of part performance in different environments. The Corps can and should build that knowledge into the TDP database to further improve MTBF and MTTR.

7. Facilities

There will need to be some facilities changes/creation in order to house “fab labs” or “maker studios” and to provide spaces in which maintenance and supply units can house 3D printing capabilities. It is the opinion of the author that every Marine Corps base with over one-thousand Marines working on it should have a “maker studio” or “fab lab” style facility in which Marines can learn about, explore, and create with 3D printing. These facilities are the catalyst by which Marine creativity can be harnessed to produce solutions to problems across the Corps. Additionally, 3D printers are not small objects and do require a certain level of protection. Units will need to set aside some space that is well ventilated, climate-controlled, and relatively free of vibrations for the 3D printers. For instance, housing a 3D printer for a maintenance platoon on the shop floor, while well ventilated, will likely cause printed parts to have tiny variations or flaws internally due to vibrations from other maintenance operations occurring in the vicinity.

C. ALTERNATE COAS

When the Marines do close down the NEXLOG AM Cell and the MCSC AMOC is effectively the lead unit in the Marine Corps for AM, they need to decide where the proposed unit (which may in fact be an enhanced MCSC AMOC) will reside in the MCSC and Marine Corps organizational chart. At present, the MCSC AMOC is a non-permanent unit nestled underneath the MCSC G-3 (operations section). Which of the functionalities described by this work should they support and pursue?

To explore these issues the author examined potential COAs. Oftentimes, commanders will request a breakdown along the lines of a Light COA, a Medium COA, and a Heavy COA, in which each has an increasing set of capabilities (and thus an increasing set of costs). In this case, it will be easiest to work from the Heavy COA down to the Light COA. Each COA describes the potential response to closing down the NEXLOG AM Cell and moving forward with an enhanced MCSC AMOC or functionally similar unit as the AM lead for the Marine Corps.

1. Heavy COA

This COA includes everything as described on the full functionalities breakdown that was shown in Figure 7. The Corps would need to add the following to the existing capabilities and functionalities.

- Robust, secured, Marine-owned and operated database, including smaller databases tied to enterprise classified networks for the printing of classified parts.
- Physical security of said database commensurate with highest classification level.

- Network controls, possibly aided by blockchain technology, to track precisely who is printing what, where, when, and how often.

- At least eight MTTs, able to assist eight units (two per MEF) simultaneously. “Train-the-trainer” style programs to create resident AM gurus in each using unit who are well versed in the capabilities and limitations of the specific printing systems that each unit owns and operates.

- At least eight systems experts working to both decide on which systems to purchase next for the Corps to enhance their capabilities, but also providing reach-back support via phone and email to using units who need assistance with the production of TDPs for existing parts or assistance with the design of novel parts.

- Robust, internal, equipped civilian engineers and scientists capable of conducting D/NDT&E of parts in comparison with OEM parts. This information needs to be embedded into the database to aid unit commanders in making appropriate risk based decisions in support of critical missions.

- At least one permanently embedded specialist at the Contracting Officers Course and at every government school that produce PMs for systems of record for USMC, DoD, and U.S. Gov’t to ensure maximum integration of AM possibilities into future PEIs and negotiate for rights to TDPs for every piece and part they buy.

- At least one dedicated, full-time legal expert.

- Corps-wide 3D printers integrated so they can spread load priority printing to the 3D printers that geographically co-located units are not currently using.

The Heavy COA has a functions analysis depicted in Figure 13, wherein functions the MCSC AMOC already has are in green and functions they would have to create and staff are in red. Yellow highlights indicate capabilities already present but which would be improved by implementing the Heavy COA.

Figure 13. Heavy COA

2. Medium COA

This COA requires slightly higher personnel overall than currently engaged with MCSC AMOC and NEXLOG AM Cell.

- One classified network tied to printers and secured appropriately to enable the printing of some classified parts, but not all of the parts that they could print if they had printers dedicated to both SIPR and JWICs. In this COA they would probably want to have 3D printing available on SIPR before JWICS, as there is likely to be a wider variety of parts available to print on SIPR.

- Four MTTs (one per MEF) thus reducing the number of units that they could simultaneously train or update to four.
- No internal D/NDT&E capability, they would be reliant on outside entities for testing.
- Increased linkage and reach back to national laboratory assets to speed turnaround time for priority Marine Corps parts.
- At least one dedicated, full-time legal expert.

The Medium COA has a functions analysis depicted in Figure 14, wherein functions the MCSC AMOC already has are in green and functions they would have to create and staff are in red. Yellow highlights indicate capabilities already partially present which would be improved by implementing the Medium COA.

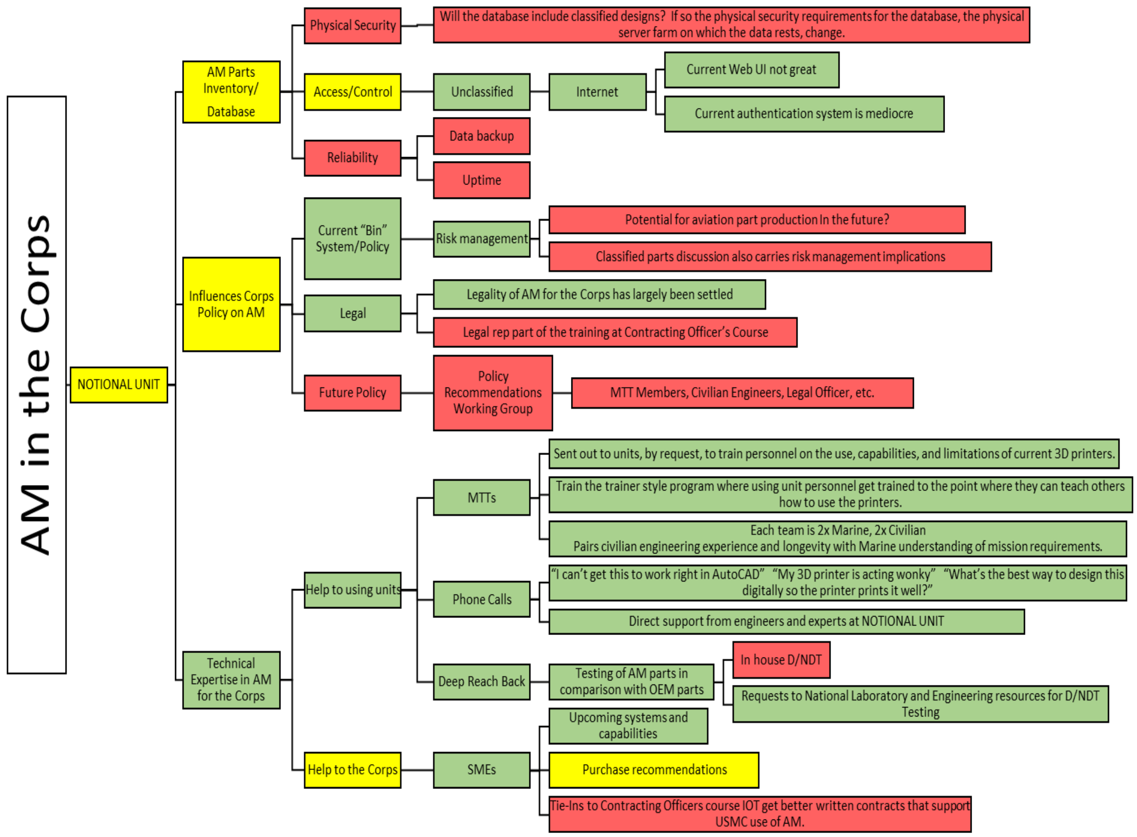

Figure 14. Medium COA

3. Light COA

This COA requires less staffing for the USMC AM Lead Unit compared to the current staffing of MCSC AMOC/NEXLOG AM Cell. It includes little internal USMC capability. If implemented, it would create a large reliance on other services and USG as a whole to progress in AM.

- Migrate all USMC TDPs to either the Army or a DoD-wide AM Database and eliminate the separate USMC AM Database. The USMC will be able to print on whatever networks the Army or the DoD writ large decide to connect to the database.
- Fewer MTTs.

- No internal D/NDT&E capability, they will still be able to utilize national laboratory resources.
- Fewest systems experts, increased reliance on USG and DoD resources.
- Fewest policy experts, essentially follow DoD-wide policy as it develops.
- One occasionally loaned legal expert.

Light COA has a functions analysis depicted in Figure 15, wherein functions the MCSC AMOC already has are in green and functions they would have to create and staff are in red. Yellow highlights indicate capabilities already present in the MCSC AMOC and NEXLOG AM Cell which would be improved upon by implementing the Light COA. The orange highlight indicates a capability that would become external to the Marine Corps if the Light COA were implemented.

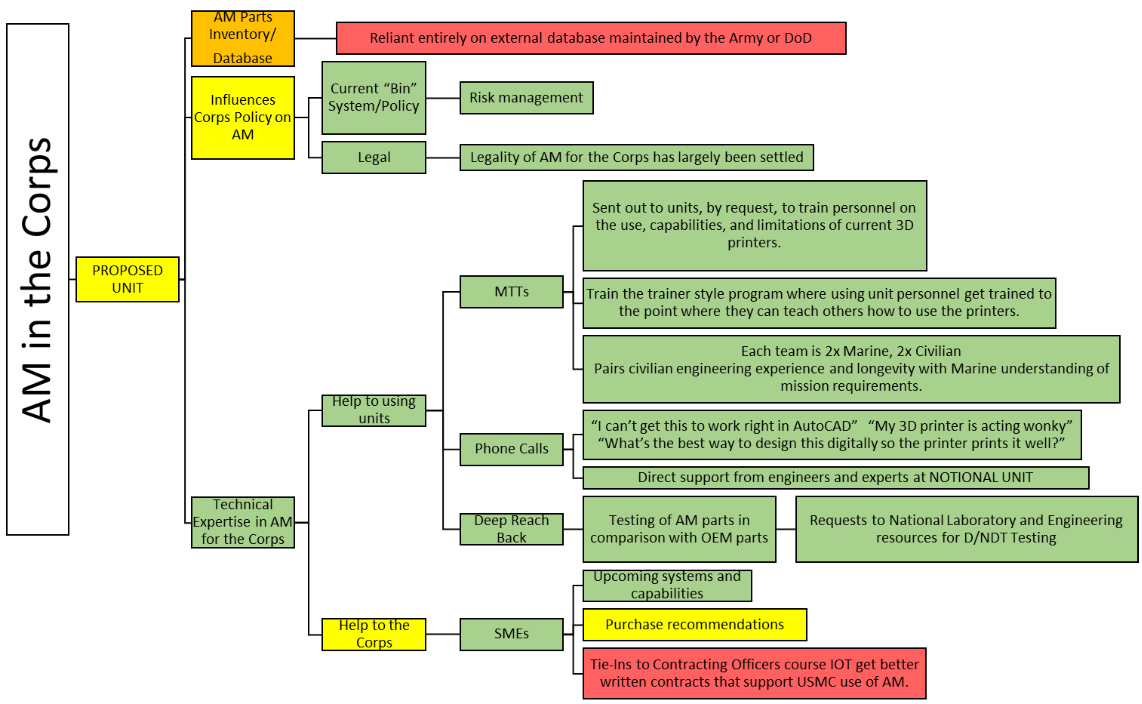

Figure 15. Light COA

D. USMC AM STRATEGY

The USMC needs to designate a lead unit, as the Army has already done, as the focal point for further efforts in AM, and fast. At present, the MCSC AMOC is in a good position organizationally and structurally to be that unit, but information on it and its capabilities needs to be publicized to the wider Marine Corps. It needs to be formally designated, by directive, as the lead organization for AM in the Corps. Figure 16 is the organizational chart of MCSC as it stands. The AMOC is added as a "current operations" element of the MCSC G-3. It does not have a program manager (PM), and it is not enshrined as a permanent unit or organization like the various PMs for other major systems of programs are. Figure 16 shows where the AMOC sits in the current MCSC structure.

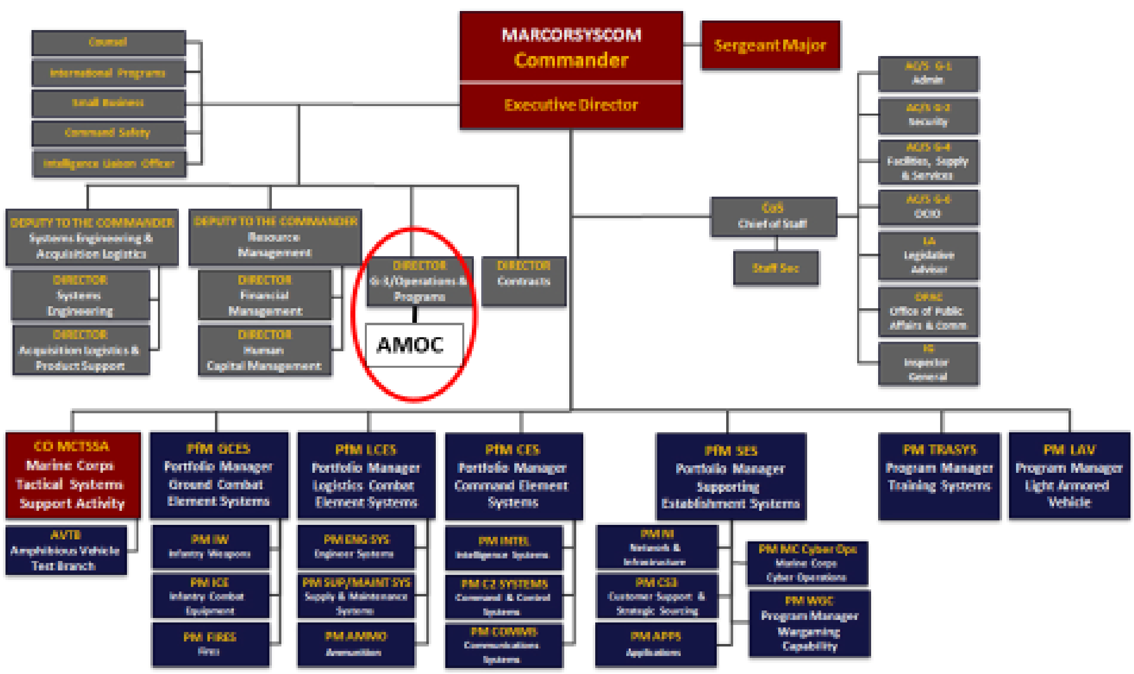

Figure 16. Current MCSC Structure. Adapted from MCSC (2018).

In order to truly cement the proposed unit (which might be an enhanced MCSC AMOC), it should become a distinct Program of Record with a PM, under the Logistics Combat Element Systems Portfolio manager. Figure 17 demonstrates where either the AMOC or a proposed unit designated as the lead unit for AM in the Marine Corps should be located within the structure of MCSC.

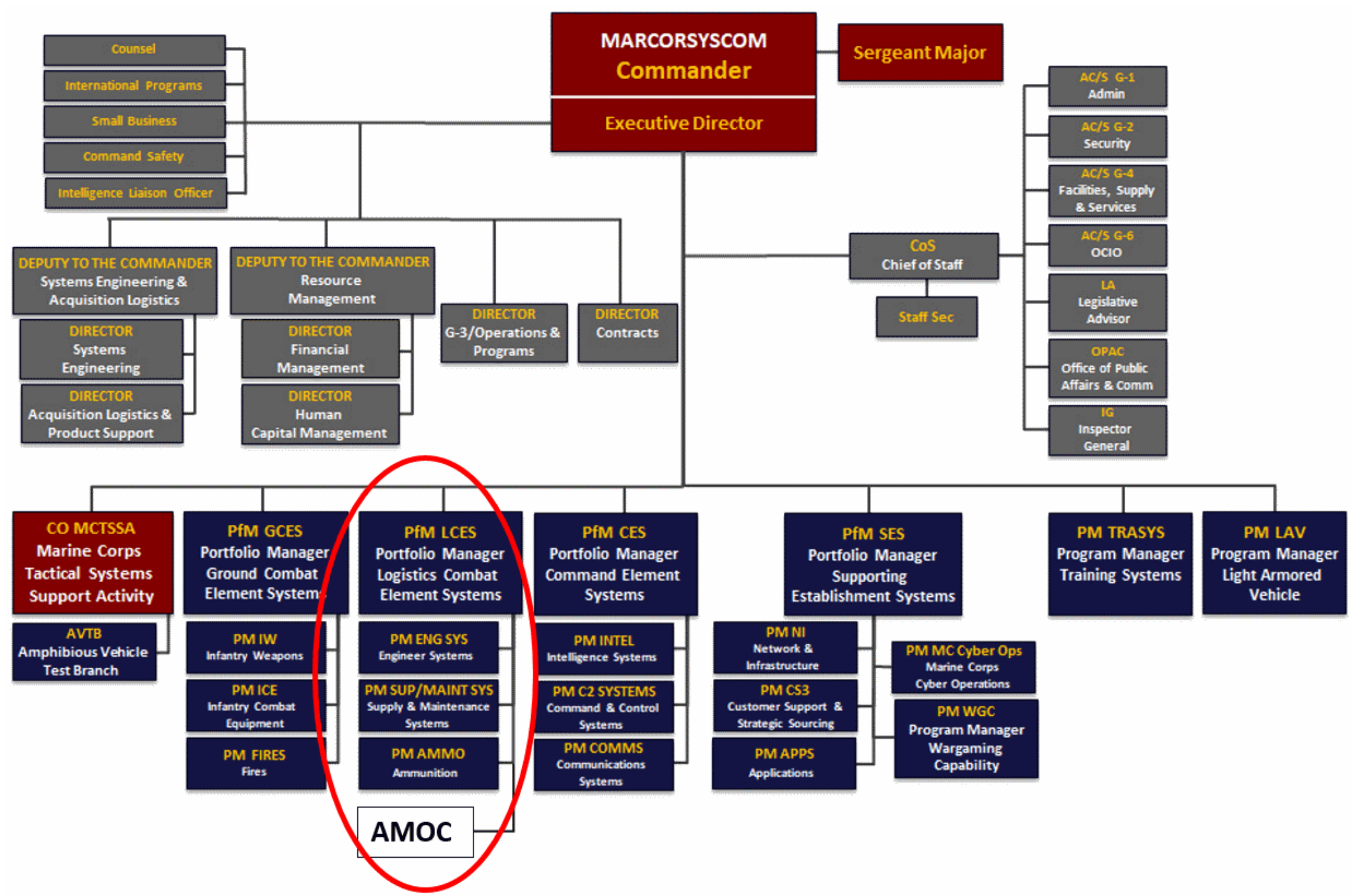

Figure 17. Proposed MCSC AMOC Chain of Command. Adapted from MCSC (2018).

The Corps needs to decide, essentially, how much of the full spectrum of AM capabilities they want to utilize. If the Marine Corps wants to utilize 100% of the capabilities inherent in AM technology, they need to implement the Heavy COA outlined above. The system of systems proposed in the heavy COA will allow for the Marine Corps to utilize all aspects of AM technology, on their own pace, with room for expansion and utilizing internal experts to assess follow-on changes. That COA relies the least on external agencies, increasing the Corps' self-reliance in this field. If the Corps is comfortable with their current level of utilization of AM technology they should implement the Medium COA, which improves on their current usage by combining additional systems into the lead AM unit without requiring large fiscal or personnel investment beyond what currently exists in the NEXLOG AM Cell and the MCSC AMOC combined. The Medium COA, in terms of organizational structure, is a reorganization that combines the two proceeding organizations (NEXLOG AM Cell and MCSC AMOC) into a more efficient system of systems delivering largely the same functionalities with a few tweaks to improve processes in the future. If the answer is that the Corps believes they are spending too much money on this field, maybe in a manner that is detracting from the mission of the Corps, then they need to choose the Light COA. If they do so, they will reduce their resource and personnel expenditure in this field but need to maintain linkages with other services, DoD, and USG's growing AM capabilities in order to augment where they are disinclined to do so themselves.

It is important to note the distinction that other Programs of Record are single-vendor led and usually have a corresponding single point of focus internal to the Corps. Even though the Corps' AM program will likely never be single-vendor or contractor led, just due to the diversity of technology, capability, and vendors in the field, they should treat it as one entity and give it a corresponding single point of focus internal to the Corps. Even if they decide to reduce their investment in the field and rely on external resources, they still need someone in the Corps to be lead for AM as indicated in Figure 17.

Eventually, if AM becomes so societally ubiquitous or is supplanted by a follow-on technology (perhaps nanotechnology), the Corps would have the option to disband this proposed unit as the focus for AM. A handy example here is the internet—when they first began to utilize the internet in the Marine Corps, the Corps needed a centralized unit to deal with integrating it in to the fabric of the Corps. As more and more units came online with it and the true extent of the capabilities inherent in it began to be explored, they strengthened that centralized unit to "run the show" for us. Inherent risks and opportunities continue to be found in the Corps' use of the internet, and they built NMCI and then MCEN as more secure, more tightly controlled networks through which they could function. Perhaps, if the use of the internet becomes ubiquitous and secure enough, they might be able to disband their enterprise networks and comfortably rely on the globally available distributed network. That is quite unlikely, and the same possibility exists for AM technology at this point. Is it secure enough? How does one track it? Who is authorized to use it? The Corps has yet to explore the full capability of AM and how it might greatly impact future operations. The author doubts that the proposed USMC AM Lead Unit will go away for a long time, but it is a necessity right now and into the near future.

E. LIMITATIONS

While the author has conducted this analysis of the functions and sub-functions of the Corps wide AM capability and its lead organization, the Corps has not stood still—MCSC AMOC's mission, personnel, and policies have continued to evolve. The author has attempted to paint a realistic and achievable way forward for the Corps and a methodology which might frame the discussion on the future of AM in the Corps. Some of these suggestions have already been implemented, not because the author suggested them but because MCSC AMOC was already working in that direction.

V. RECOMMENDATIONS

A. ACTIONS FOR THE MARINE CORPS

I recommend the Corps pursue the Medium COA with regard to AM. As a Marine, I believe the Marine Corps needs to maintain a level of self-reliance comfortable for the Corps. The structure of the current MCSC AMOC is at least an 80% solution at present—they need directives pointing to them and appointing them as the USMC lead for AM, and they need a plus up (mostly of personnel) in a few areas in order to realize the potential of AM in the Corps. One of the best resulting benefits of staffing the MCSC AMOC/proposed USMC AM Lead Unit with civilian scientists and engineers is the ongoing analysis that could be conducted. At the end of the day, Marines will go on to their next assignments—but dedicated civilian professionals that live and breathe AM could and should be tasked with finding even more specific ways to improve the Corps' use of AM in the future. The proposed unit should be self-reflective, conducting internal analysis on the usage rate of, for example, MTTs, and adjusting staffing based upon demand. The Corps needs a dedicated group of professionals working year round to provide a dim-sum style cart of AM options and capabilities for the Marine Corps to choose from based on cost, personnel constraints, and mission requirements. Abandoning the Corps' own internal progress in the field of AM and relying upon DoD and OGAs for AM direction might potentially provide cost savings, but this path would not allow the Corps to truly explore how AM might specifically benefit the Corps' unique mission. As this field continues to evolve, the Corps should endeavor to follow the cutting edge of AM. They should be willing to take risks and test equipment in ways enabled by AM; however, they need to simultaneously provide their commanders with the appropriate information required to make quality risk-based decisions.

B. FUTURE RESEARCH

This thesis is based, in large part, on research already conducted in the field of AM, especially research focused on assisting the Marine Corps with the future of the technology. This thesis aims to provide a way forward for the Marine Corps in terms of organizational structure to enhance and progress the Corps' use of AM technology. At the completion of this thesis there are four areas requiring additional research.

1. What should the future USMC TDP repository look like? How should it function? How should it be administered, in terms of both technical means and access control?

2. Further research is needed on the cost benefit balance for internal D/NDT&E. That is an area the Marine Corps is light in right now, reliant on external USG labs and paying them for their time, and they are still not able, yet, to provide risk information to commanders with sufficient speed and accuracy. Commanders need to be able to trust the data they get (or generate themselves) because it can mean life or death for Marines and Sailors. Internal D/NDT&E is the most costly effort considered in this work, but can provide the greatest reward to the Corps long term.

3. Research needs to be undertaken on how best to fully integrate AM capabilities into existing and planned GCSS-MC modules.

4. Research needs to be conducted to find the tipping point between decreased MTTR/increased MTBF caused by in situ utilization of AM technology and resource cost to the Corps' supply system. 3D printers need material to print with, and that material must be of sufficient grade and quality to be useful, especially when printing sensitive or delicate parts. At some point it is likely more efficient to continue to produce certain parts or whole categories of parts in traditional manufactories in the continental U.S. versus printing them in situ at using units. There will be trade-offs required here, and the trade space needs to be carefully explored.

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