Additive Manufacturing for Sustainment:

Challenges and Opportunities

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The authors would like to thank Colonel Keith Bearden, PhD, Deputy Director of the Engineering and Technical Management organization-- Air Force Material Command, for his time and input.

The authors would like to thank Kyle D. Hedrick, P.E. Defense Logistics Agency, Aviation Engineering, for his time and input.

The authors would like Greg Kilchenstein, Director of Enterprise Maintenance Technology- Office of Secretary of Defense -- Logistics and Material Readiness -- Maintenance Policy and Programs for his time and input

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Fuel Nozzle and Bracket Images on the front cover courtesy of General Electric

1.0 Introduction

Additive Manufacturing (AM) has the potential to **improve** the **Mission Readiness** and **Availability (A_o)** of **Department of Defense (DOD) systems** by revolutionizing the sustainment and maintenance of these systems through the rapid production of replacement components at a reduced total cost of ownership[1]. However, **AM in its current state is not capable of meeting sustainment and maintenance requirements**. Significant **changes in current policy, procedures[2] and technology[3] are required for AM to achieve economic[4] viability** for a vast majority of the[5] potential components in the DOD supply chain.

In addition, **there are hundreds if not thousands of opportunities[6] that could be addressed using current AM technology[7] with little or no investment** that would supply the warfighter with currently unsourced components at potentially reduced cost and production lead times.

Figure 1: AM produced Injection Molds (EOS, Inc.)

In order to achieve an optimal outcome, a focused and coordinated development effort between the military services and the supporting DOD agencies needs to be initiated. This effort must **holistically identify and implement changes[8] to the policies, procedures and technologies required for the services to achieve Mission Readiness at an affordable total cost of ownership.**

AM is not a replacement for current manufacturing methods, but rather another approach to augment them, as it can be used to perform multiple manufacturing operations such as, rapid prototyping, tooling, and production and repair of finished components.[9]

1.1 The Need

In order for AM to successfully address the needs of the DOD services, an AM system[10] needs to be developed that is available, affordable and executable by the services maintenance

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[1] Some of these benefit can also be achieved through Rapid Manufacturing using convention manufacturing approaches.
[2] Current Engineering Support Activities (ESA) process results in a negative Return on Investment (ROI).
[3] Current AM technology does not have sufficient repeatability and quality assurance; technology is not robust enough for deployment.
[4] Current Selective Laser Sintering and Electron Beam processes are too costly for adoption by tier 3 OEMs.
[5] 4.5 Million parts in DLA database per LMI study presented at 2015 Defense Manufacturing Conference (Tom Parks presenter). However, many of these entries are non-additive manufacturable parts such as fuel, food stuffs, etc
[6] Such as Non critical components, Tooling (e.g. injection molding & blow molding) and repair.
[7] Use AM to create injection molding tooling and produce gaskets and seals using specified materials and processes.
[8] AmericaMakes has begun a technology roadmapping effort to coordinate key DOD agencies
[9] Depending on materials and application net-shape or near net-shape manufacturing can be achieved.

and logistics organizations, and Original Equipment Manufacturer (OEM) contractors down to the tier three (3) level. This requires addressing appropriate policies and procedures to ensure they are consistent and flexible enough to support future AM technology, and create an economically viable process. Specifically, the following areas need to be addressed[11]:

- **Policies and Procedures:** This aspect includes a wide range of activities that encompass everything from DOD guidelines to streamline and standardize the implementation of AM to the actual workflows that carry out the AM process. These workflows include identification of candidate components and development of the Technical Data Package (TDP) for the approval of AM production. Most of the sustainment and maintenance components used by DOD are procured by the Defense Logistics Agency (DLA). However, the engineering authority to accept the use of AM resides with the services and the process to qualify and approve the use of AM must be streamlined to meet the individual services requirements.
- **Economics:** In order to be successful, an AM development effort must achieve Mission Readiness for the services at an affordable Total Cost of Ownership (TCO). This includes the cost of: purchasing and operating an AM system; the impact on the cost of logistics such as procurement, warehousing and shipping; and the impact on the cost of operating, personnel training and maintaining the impacted systems.
- **Technology**: Any AM approach current or future must simultaneously address the design and analysis, materials and manufacturing system[12] aspects. The AM approach must also address affordability, persistent quality assurance[13] and repeatability and use an open architecture system[14].

1.2 Desired End State

The desired goal of an AM development effort should be to ensure that it is available, affordable and achievable by Tier three (3) (OEMs) that support the DLA supply chain and the military services for use in their logistics depots and forward basing locations[15]. By achieving this goal, AM can provide DOD with the following:

1. Provide the services with the ability to make parts on demand to maintain Mission Readiness of key systems.

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[10] The AM system must perform the following: (1) deposit material to be fused, (2) In a controllable manner discretely fuse together precursor materials, (3) Achieve process sensing and control during operation and (4) establish environmental control to ensure optimal processing conditions and health safety of the operator

[11] Other issues may need to be addressed as well.

[12] Material fed vs material bed, laser versus electron beam or other.

[13] Monitor and/or control the AM fabrication throughout the entire process, not just a post process inspection.

[14] Reduce the cost of future upgrades.

[15] Technology needs to be comparable to 3 axis CNC machining in terms of cost, implementation and ease of use.

2. Reduce per unit production costs[16] and reduce inventory costs due to lower costs for smaller sized production runs and reductions in production lead times.
3. Meet on demand production for surge Mission Readiness requirements[17] through a virtual manufacturing network to produce demand critical parts in parallel production efforts at multiple vendors or Government facilities.

1.3 Approach:

In order to achieve the desired end-state and an economically viable approach to AM, the technical, policy and procedural issues that drive and regulate the use of AM must be holistically addressed. To achieve this, a design of "*systems of systems*"[18] must occur. For the last twenty years, the services and the OEM Primes have performed studies using AM produced representative parts such as aircraft bulk heads, landing gear components and most recently fuel nozzles for jet engines.[19] The purpose of these studies has been to develop best practices to adapt current AM processes in a manner that minimizes their short comings for production.[20] What is needed is a **Quality Function Deployment (QFD) type strategy to establish the key metrics and requirements for policies and procedures, and economic viability/technology capability** that will enable the desired end-state described in section 1.2. By doing this, a DOD-wide strategy can be implemented that will result in the **lowest cost** at the **fastest implementation** rate with the **greatest possible capability to meet Mission Readiness**.

2.0 Policy and Procedures

One of the critical factors to be addressed is the coordination between the military services (engineering authority), DLA (procurement), OEMs (geometry definition & design intent) and component fabricators[21] (production). In order to accomplish this a DOD level policy is going to have to be created that establishes requirements on the exchange of critical data and information and streamlines the approval process based on technical maturity and benefit with

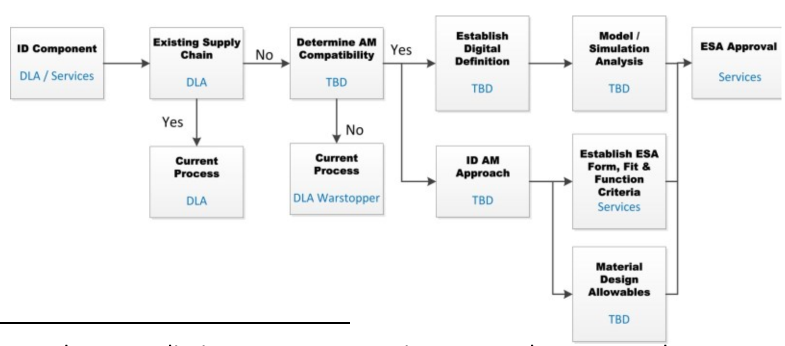

Figure 2: Potential process for procuring sustainment components using Additive Manufacturing

[16] AM reduces or eliminate non-reoccurring cost such as set up charges or tooling that get amortized over the production run
[17] Such as wartime operations
[18] Policies, procedures, technologies and data management systems.
[19] These efforts were similar to many of the current efforts being proposed now.
[20] With respect to the form, fit and function.
[21] Tier 3 OEMs or Services logistics and maintenance facilities.

respect to Mission Readiness and economic considerations. Furthermore, If AM is going to have a substantial impact on sustainment and maintenance, the process for converting and approving the use of AM on parts in the DLA database must be streamlined and sped up. Additionally, the **development of a digital thread[22] is a requirement** to tie together all these organizations with the required information in a timely manner.

2.1 Identify Candidate AM Parts

Identification of candidate AM parts is a critical task because AM is not always the best approach. Technical and economic considerations (i.e. business case) need to be considered with making the decisions to use AM.[23] Often times if a component can be produced using conventional manufacturing[24] methods it is usually the lower cost approach compared to AM. Furthermore, a return on investment (ROI) should be considered if the use of AM will require additional costs related to qualification and testing. Some of the technical considerations that must be accounted for are the ability of the chosen AM approach to achieve the required form (shape), fit (size and tolerance) and function (mechanical properties[25]) and the ability to substitute AM compatible materials for the original materials.[26] In addition, environmental factors[27] and the ability to inspect these components[28] must be considered. From an economic standpoint, AM with its production rate independent cost structure is well suited for sustainment and maintenance applications of extremely low rate production parts. However, limited material deposition rates and the use of more expensive raw materials often increases the production cost. Methodologies such as "Rib on Plate" [29] can be implemented to reduce costs through the use of lower cost stock materials and the AM fabrication of only the component's complex features.[30] Finally, automated processes such

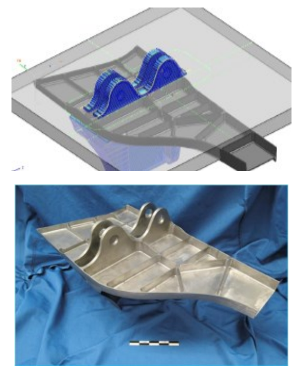

Figure 3: Example of Rib on Plate (Lockheed Martin)

[22] Digital Thread and Digital Twin are current DOD efforts to tie together critical information regarding military systems as a way to lower the cost of life cycle management.
[23] Business case will depend not only on total cost but also impact on Mission Readiness
[24] A qualified vendor is available and willing to produce the part.
[25] Static, dynamic and fatigue properties of AM components are typically very different than conventionally manufactured components of the same material system.
[26] Materials such as many aluminum alloys are not processable via Laser based AM methods due to reflectivity of the laser. In addition, the AM processing conditions of a lot of common aerospace materials have not been developed.
[27] Such as galvanic corrosion or mechanical performance at low or high temperature.
[28] Use of Non-Destructive Evaluation techniques such as x-ray can be difficult on complex geometry parts.
[29] Rib on Plate- refers to the practice of using AM to build features on stock materials (plates, C-Channel, etc) to achieve design intent at the lowest cost and fastest time.
[30] Candidate components for "Rib on Plate" include bulkheads, spars, longerons, brackets, etc.

as database searches of the supply systems and stock parts will not identify the mission readiness critical manufactured parts required to support the systems going through programmed depot maintenance.[31]

2.2 Creation of the Technical Data Packages

Technical Data Packages (TDPs) are required for the acceptance of AM in sustainment and maintenance applications because they not only provide a geometric definition of the component to be fabricated; they also add the context with which the component will function.[32] This context is needed by Engineering Support Activities (ESA) to validate the use of AM in a particular application. Unfortunately, a vast majority of the systems currently in use were created prior to the advent of CAD design tools and finite element models and simulations. As a result, the only documentation of the original engineer's design intent resides in two dimensional drawings, drawing notes and design notebooks, but often these sources are unavailable.

If geometry definition does not exist, the maintenance and sustainment community has two choices. The first is the manual creation of 3D geometry based off the drawings. The second is the use of reverse engineering metrology tools[33] to create the CAD definition.[34] Both of these methods are manually intensive and can be costly.[35] As a result, a standard for the creation of a TDP needs to be established.[36]

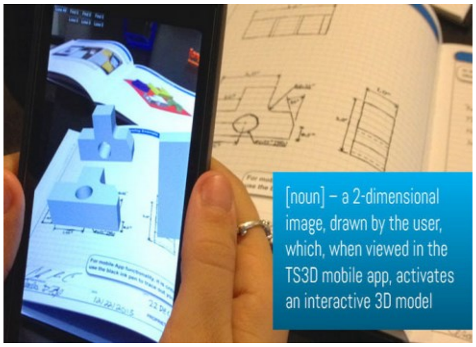

Figure 4: Advanced scanning technology to create 3D CAD models from drawings (Tangible Solutions) [29]

Ownership of data rights or intellectual property is another issue to be resolved. In some cases, the US government (USG) has complete ownership of data rights of the TDPs associated with the components of interest. In other cases, the original OEMs still own the rights to the TDPs. The issue arises when the services need a small production run to meet its sustainment needs, but the run is so small it is not economically viable for the OEMs to fabricate. Potential solutions would be to license the data rights from the OEM in the event they were not capable of producing the

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[31] A recent development effort to use database search to identify candidate AM parts only netted 44 candidate parts out of possible 4.5 million components.
[32] Environmental conditions, mechanical loading, duty cycle, etc.
[33] Such as Coordinate Measuring Machines (CMM), CT scanners, laser scanners, etc,. A majority of the Service Depots have the engineering capability to reverse engineer and create the 3D CAD models.
[34] CMM scanning does have limitations in terms of tolerances and cannot address issues if the scanned part is off nominal tolerances in its build. The tools are available at most maintenance depots.
[35] Another possible approach would be the development of scanning technology that could convert 2-D drawing data into a 3D CAD format that could be easily manipulated to produce the exact digital definition. Technology has been notionally demonstrated but would need further development work.
[36] Define requirements for business case, geometric definition, manufacturing requirements, use case, duty cycle and analysis.

components at a reasonable cost or to pay the OEMs to create and maintain the TDPs for use by the government at a later time.[37]

2.3 Repeated Assurance of Form, Fit and Function

AM in its current technical state poses a greater challenge than any other manufacturing process in repeatedly producing components that meet the intended form, fit and function with respect to both general dimensions and tolerances (GD&T), and mechanical properties. Both of these issues are the result of the current technology state[38] of AM and the **inability to perform closed loop control** with respect to controlling geometry and processing conditions that determine mechanical properties. A significant amount of **technical research has been done** in these areas but **additional research is need if AM is to be used on safety critical parts.**

From a policy and procedure perspective, an adaptable policy will need to be created that established the procedures required to assure each component meets form, fit and function requirements. This will include things such as coordinate measuring machine (CMM) inspection and non-destructive testing and inspection. The criteria for these tests and inspections should depend on the current and future technical capability of AM to control geometric tolerances and material properties.

2.4 Environmental, Health and Safety

The environmental, health and safety aspects of AM are the safe use and handling of high powered lasers and powdered metals. High powered lasers[39] are currently used in industrial settings and have established procedures to ensure their safe use. **Powdered metals** particular those used in selective laser sintering processes and having an average diameter of 50 microns[40] or less, **pose two safety concerns.** The first is **inhalation** which over time may lead to health issues.[41] The second is an **explosive hazard**.[42] One potential way to avoid this issue is the use of wire or filament feed stocks during the AM process.

2.5 Engineering Support Activities (ESA) Approval Process

The ESA process is perhaps the most challenging aspect of the policies and procedures aspect because it involves the authority, responsibility and accountability to ensure that the impact of using AM will not be detrimental with respect to safety or operational use.

[37] Boeing is already providing this service to DOD

[38] Result from the inability to control thermal stresses, surface tension in the melt pool and other AM processing conditions.

[39] Used for laser cutting and welding

[40] Are similar to powdered metals used in ammunition and are classified as a Group D explosive and must be handled accordingly to DOD guidelines (DOD Contractor's Safety Manual for Ammunition & Explosives) DOD 4145.26-M

[41] Lung cancer in a manner similar to asbestos.

[42] Aluminum and Titanium powders are pyrophoric and can catch fire with exposure to water.

For the successful use of AM, the ESA process must ensure the following has occurred or is in place:[43]

1. **Process Stability**: The AM process chosen is consistent in its ability to meet the form, fit and function, and has predictable costs.
2. **Producibilty:** Current and future AM production runs can be achieved without adversely affecting costs and/or quality.
3. **Development of Design Allowables:[44]** Material property characterization and investigation extensive enough to prevent the failure of the component due to the use of AM.
4. **Predictability of Performance:** Demonstrate that modeling, simulations and testing methodologies have the ability to accurately predict the performance of the AM process specific to the application in question. This will verify and validate the modeling and simulation efforts carried out during the creation of the TDP.
5. **Supportability:** The thermal, environmental and mechanical deterioration of AM produced materials is understood and acceptable from a quality standpoint and cost effective preventive methods and /or in-service repair methods are either available or can be developed in a timely manner.

The process for gaining approval from the technical authority for the use of AM on a particular component will most likely depend on the specifics of the application and the particular parties involved. Given the potential number of components that could benefit from the use of AM in sustainment it is recommend that a **criteria based process** be approved to **establish thresholds for analysis and approvals required to implement AM.[45]**

2.6 Common Standards and Practices for AM

One of the key requirements for success of AM is the establishment of standards to achieve industry wide consistency in the manufacture of components. This is particular important in the case of AM because many of the inputs and processes that determine quality[46,47] in conventional manufacturing occur in a serial manner that limits their impact on the other quality criteria. In AM, the thermal and final shape processing happen concurrently, while factors such as geometry, build rate and volume have an impact on both mechanical properties and geometric

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[43] Based on standards and definitions established in the Air Force Airworthiness Bulletin (AWB-1015) 15 Jul 2015, terminology and methodology may vary.

[44] Development of A-basis and B-basis allowables consistent with Mil Handbook 5 / 17 methodologies.

45 Example use of AM to make fixtures and tooling should have a less rigorous and intensive approval process than critical structure components.

[46] Consistency of final performance (mechanical behavior, dimensions and tolerances) or states (chemical composition, environmental behavior).

[47] Certifications for raw materials, processing parameters and heat treatments occur at mills, while NDE and GD& T inspects occur post manufacturing. In AM these inspections and certification will need to be done during and after the AM processing.

dimensions/tolerances.[48] As a result, the standards developed to address AM common standards and practices need to take these considerations into account.

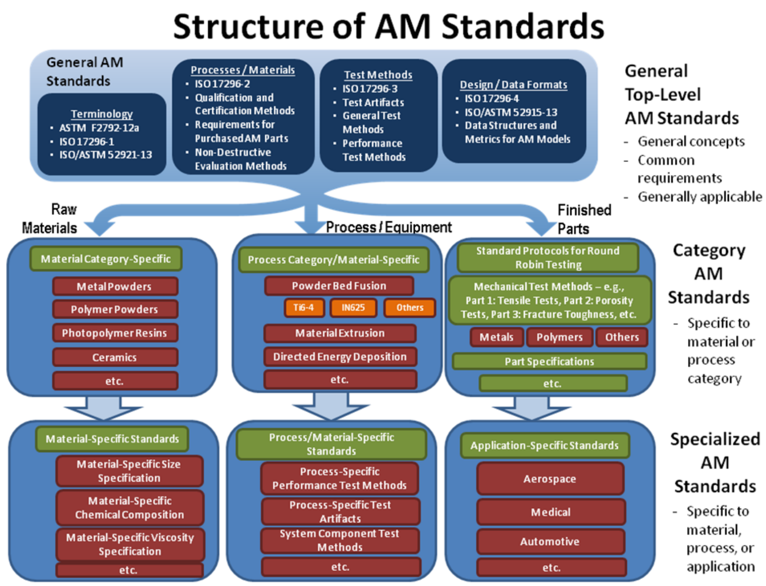

Figure 5: ASTM F42's hierarchy of AM standards

The organization that is taking the lead for the development of standards for AM is the American Society for Testing and Materials (ASTM) through their ASTM F42 committee on AM. The intent of the committee is to establish an international standard in the areas of terminology, Processes and Materials, Test Methods and Design and Data formats. As part of this, the F42 committee has established a three level hierarchy of standards. The first is a set of general standards that generically apply to most, if not all off the various types of AM processes. The second is category standards that apply to a specific material or process category such as a material category (i.e. titanium) or process category (i.e. selective laser sintering). Finally, specialized standards will be established that are specific to a material system (i.e. Ti 6-4), process (i.e. direct metal laser sintering) or application (i.e. flight critical structure). From these efforts, critical aspects of AM such as the development of material design allowbles, best practices for testing and non-destructive evaluation of materials and specifications for AM processing will be devised.

It should be noted that other organizations such as AmericaMakes and commercial companies are also developing internal standards and best practices for AM processes and mechanical properties. As a result, efforts should be taken to ensure that the gaps in the standards be rectified without duplication of effort.

2.7 Challenges in Implementing Policy and Procedural Changes.

The primary challenges to implementing the policies and procedures required to utilize AM in sustainment and maintenance is the fact that AM is a new and disruptive paradigm. Typically, new paradigm changes are met with skepticism and resistance. Unless a DOD level policy is introduced that addresses this the implementation of AM for sustainment can be stymied significantly. The second major challenge to implementing AM is the lack of sufficient skilled manpower and funding. The collective talent pool required to approve the use of AM must be technically skilled in AM processing, Material Science and Engineering. Given the relatively

[48] Each AM system can be considered to be a "micro-foundry".

recent development of AM technology experienced personnel such as skilled technicians can be hard to obtain. In addition, lack of funding has already been identified as a limiting factor in the current ESA process and often prevents the implementation of changes that would lower cost and/or production time of current maintenance and sustainment components. **A potential resolution to these challenges is the creation of a DOD policy that established a streamlined and standard process that encompasses all aspects of component identification, TDP creation and ESA approval, and ties together the activities of DLA partnering with the services.**

3.0 Economic and Affordability Considerations

Success in the use of AM for sustainment and maintenance requires the achievement of Mission Readiness at an affordable Total Cost of Ownership (TCO). This includes the cost of building support infrastructure, manufacturing, logistics and operations associated with the use of AM to produce sustainment and maintenance components.

3.1 Support Infrastructure Costs

In order to identify, analyze and approve the use of AM on sustainment and maintenance components, an information management infrastructure needs to be established that generates and shares the required information and data. The backbone of the infrastructure is the digital thread. The digital thread will be used to link together the artifacts created from identifying the component for AM, creation of the TDP and the ESA that approve the use of AM.

Digital Thread and Information Technology (IT): Digital thread and its associated effort digital twin are broad DOD efforts to lower life cycle costs in all aspects of a system's life.[49] Because the effort in digital thread is relatively new and the need to create and share technical information is required, initial AM sustainment and maintenance parts may have to bear some of the effort to create their own digital thread. This will require the identification, planning, resourcing, acquiring facilities, hardware, software, documentation, manpower, and personnel necessary for planning and management of computer hardware and software systems.

In addition, the services will need to identify, plan, resource, and implement management actions to develop and acquire information;

- to operate, maintain, and train on the equipment to maximize its effectiveness and availability;
- effectively catalog and acquire spare/repair parts, support equipment, and all classes of supply;
- to define the configuration baseline of the system (hardware and software) to effectively support the Warfighter with the best capability at the time it is needed.

Component Identification and TDP Creation: The process to identify a component for AM and build the subsequent TDP is a manually intensive effort because it requires a detailed

[49] From conceptual design to end of life including sustainment and maintenance.

understanding of AM capabilities along with the specific life cycle requirements which are unique to every component. These efforts would result in a onetime sunk cost.

In addition, there will be a significant amount of capital infrastructure that will be required. In order for AM to be implemented DLA and the services must do the following:

Maintenance Planning: Identify, plan, resource, and implement maintenance concepts and requirements to ensure the best possible equipment/capability is available when the Warfighter needs it at the lowest possible life cycle cost.

Manpower and Personnel: Identify, plan, resource, and acquire personnel, civilian, and military, with the grades and skills required:

- to operate equipment, to complete the missions, to effectively fight or support the fight, and to win our Nation's wars;
- to effectively support the Soldier and to ensure the best capability is available for the Warfighter when needed.

Facilities: Identify, plan, resource, and acquire facilities to enable training, maintenance, and storage to maximize effectiveness of system operation and the logistic support system at the lowest life cycle cost. Identify and prepare plans for the acquisition of facilities to enable responsive support for the Warfighter.

Training and Training Support: Plan, resource, and implement a cohesive integrated strategy to train military and civilian personnel to maximize the effectiveness of the doctrine, manpower and personnel to operate and maintain the equipment throughout the life cycle.

Packaging, Handling, Storage, and Transportation (PHST): Identify, plan, resource, and acquire packaging/preservation, handling, storage, and transportation requirements to maximize availability and usability of the materiel to include support items whenever they are needed for training or the mission.

3.2 Manufacturing Costs

The key for **DOD to obtain the lowest Total Cost of Ownership** possible through AM is to **ensure that AM is affordable by the organizations that will use it** in production. In this case, that is predominately Tier 3 OEMs[50] and the maintenance and logistic organizations of the services. Affordability[51] can be broken down in to two areas:

[50] Small business sized machine shops.
[51] Affordability is a relative term and depends on the specific organization involved.

AM Product System Purchase Cost: Current production AM systems can cost upwards of $500K for a polymer based system[52] and over $1M for a metal based system.[53] Typically, this is too much for a Tier 3 OEM to afford especially when an initial low utilization rate will reduce the return on investment. To address this, multiple companies have introduced hybrid powder fed AM systems with three and five axis CNC machining systems as a way to improve utilization rates and speed up overall manufacturing time. However, because some of these systems start at $2M they may not be affordable for Tier 3 OEMs or widespread use in DOD logistics infrastructure.

Figure 6: Optomec LENS AM- CNC hybrid manufacturing system

Re-occurring costs: One of the drawbacks to **AM** is that it **has high reoccurring costs compared to conventional manufacturing.[54]** Processes such as selective laser sintering require special powders that are often five to ten times the cost of the base material.[55] Also, these processes are laser based[56] and will require significantly more power than conventional manufacturing processes need to achieve similar results.

The key to **widespread adoption of AM** production systems by the Tier 3 is the technical **development of a low cost AM manufacturing system** that **minimizes procurement and operational costs**.

3.3 Logistics Costs

AM based production has the ability to lower logistics costs. This is based on the fact that AM can generally produce components in a faster time than conventional manufacturing and allow for true "just in time" production runs which result in the following:

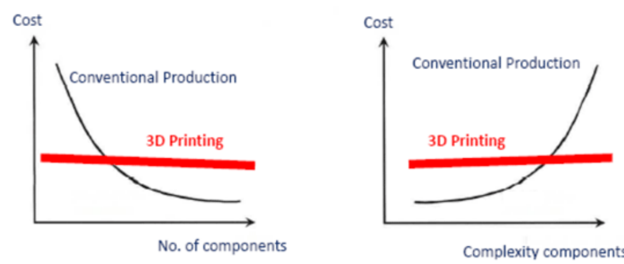

Figure 7: Per unit production cost of AM (3D Printing) vs Conventional Production base on number of components built and complexity of design

Procurement Costs: Because AM results in production rate independent per unit manufacturing costs, the expectation is that there will be cost reduction compared to conventional manufacturing of sustainment and maintenance components, because they are typically small volume production runs.

Reduced Inventory Carry Costs: By reducing the time it takes to replenish the stock on Mission Readiness critical components the DLA and services can reduce the amount of

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[52] Such as Fused Deposition Modeling (FDM) or polymer jet printing.
[53] Such as selective laser sintering, electron beam additive manufacturing or Laser Engineered Net Shape (LENS).
[54] AM reduces other non-reoccurring cost such as tooling and can result in a net overall cost savings.
[55] Gas atomized Titanium 6-4 powders cost between $150 to $300 per pound, where the equivalent grade welding wire is between $30 to $50 per pound.
[56] Lasers are between 10% to 20% efficient in converting input power to output laser energy.

inventory needed on hand in order to ensure a constant supply. This will in turn reduce the warehousing requirements and associated carrying costs.

Smaller Logistical Footprint: The use of AM in forward deployed locations or at sea will significantly lower the logistical requirement in terms of both volume and weight of materials that must be deployed. Instead of bringing high value finished replacement components to the theater, lower cost and more transportable raw materials can be shipped instead.[57,58,59]

In order to achieve this, the services must implement the following:

Supply Support: Identify, plan, resource, and implement management actions to acquire repair parts, spares, and all classes of supply to ensure the best equipment/capability is available to support the Warfighter or maintainer when it is needed at the lowest possible life-cycle cost.

Support Equipment: Identify, plan, resource, and implement management actions to acquire and support the equipment (mobile or fixed) required to sustain the operation and maintenance of the system to ensure that the system is available to the Warfighter when it is needed at the lowest life-cycle cost.

3.4 Operational Costs

This includes costs that are associated with the impact of using AM to perform maintenance and sustainment by the services. The main factors to consider are the cost associated with operation costs and downtime of the systems in need of replacement components and the affect that has on Mission Readiness.

Mission Readiness: The cost of downtime and the impact of Mission Readiness for the military services can be difficult to quantify. But there is no question that downtime affects the operational capability and readiness of the military units when a system is no longer available due to a shortage of spare parts. The possibility that AM can produce components in a "right time and right place manner" will have a positive outcome on the Mission Readiness of the services and to the Warfighter.

Operational Costs: The use of AM cannot adversely impact the operation of the component in question and thus induce further cost due to operational limits[60] or life cycle and/or life span reduction[61]. However, one area were AM might be able to reduce operational costs is the repair of wear items in lieu of replacement.[62]

3.5 Factors Influencing Cost Considerations

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[57] NASA has already demonstrated this by sending a "makerbot" printer to the International Space Station to print miscellaneous parts. Some technical work remains to ensure that AM production can occur in a more rugged and hostile environment such as on a ship at sea or forward base.

[58] Requires use of an ESA approved TDP that specifies design, materials and processing requirements

[59] Additional systems to perform post processing heat treat will likely be required

[60] Weight growth due the use of AM on an aircraft parts could reduce aircraft range or increase fuel consumption for a given mission.

[61] Increase in maintenance cycles due to reduction in fatigue life.

[62] Developed by Pratt & Whitney in the 1970's, Metal additive manufacturing got its start as a laser cladding process to repair jet engine turbine blades.

The **current and future cost** of AM manufacturing is primarily **driven by technical factors**. Development of **AM technologies** and techniques **to increase material deposition rate, improve material performance, quality and lower manufacturing costs** will have the biggest impact in **reducing the overall Total Cost of Ownership** of AM produced parts.

4.0 Technical Considerations and Opportunities

The continued **development of AM technology** is the biggest challenge and opportunity with respect to its use in sustainment and maintenance. AM technology must **simultaneously reduce the total cost of ownership and ensure a safe and effective implementation.**

As noted before in its current state AM still offers a tremendous but untapped opportunity in sustainment and maintenance in area such as:

1. The production of non-structurally critical parts such as knobs, handles, wire harnesses and other non-critical parts.
2. The use of AM to make tooling for injection molded parts such as rubber gaskets, faceplates, seals or safety covers (e.g. stick and throttle covers).
3. Repair of tooling and wear items components.

In order to optimally develop AM from a cost and performance perspective **a holistic and systematic perspective needs to be taken** in order to determine the methods, approaches and technologies that need to be addressed. Future AM production systems need to account for the impact of their processes on the designs and materials that they may enable or exclude. In a similar fashion, design for additive manufacturing[63] approaches must be producible using available manufacturing systems and materials. Finally, materials need to be developed and qualified that are compatible with manufacturing processes and have consistent mechanical properties that allows for accurate analysis of the designs.

To date several technical challenges have been identified as currently preventing AM from achieving its optimal potential.

4.1 Lack of Consistent Mechanical Properties:

Reported mechanical properties of AM produced components in metals and polymers have varied greatly. Metals, in particular, have mechanical properties that have varied from being similar to cast properties to greater than wrought. As a result, these variations prevent the use of AM produced materials in structural applications. For the most part, the mechanical properties of metals are dependent upon their microstructure. Microstructure is dependent upon chemical composition of the metal alloy and the thermal processing[64] the metal undergoes. These variations in mechanical properties are in part due to changing geometry and environmental

[63] Design for Additive Manufacturing is not as big of a factor for sustainment components as it would be for new production design because the form, fit and function is already established.
[64] The initial cooling rate plus any subsequent heating and cooling drive grain structure.

conditions[65] that occur during the AM build process, as a result, variations in microstructure and thermal stress may occur. *Potential Solution: The development of a persistent in situ process monitoring and control system that manages the mass- thermal balance of the AM build process.*[66]

4.2 Variations of Geometric Dimensions and Tolerances:

Similar to the variation in mechanical properties, current AM technology has issues with consistently producing components with repeatable dimensions and tolerances. The issue is driven by thermal and geometric issues. Thermal stresses and expansion caused by the repeated heating and cooling cause physical distortions during the build process. Variations in the geometry of these parts further compound the issue. *Potential Solution: There are currently research efforts on going for predictive modeling of thermal driven distortions. The intent is to update the path planning of the AM production machine. In addition, adaptive machining approaches*[67] *could be incorporated to account for and correct variations as they occur.*

4.3 Build Volume Scalability:

Build volume scalability has been identified as another potential issue with current AM production technology. Typical build volumes for commercial polymer and metal based systems are typically on the order of 1 cubic foot (12" x 12" x 12") and while this build volume is sufficient for many applications such as biomedical implants it does provide some limitation with respect to DOD applications. The technical hurdle with scaling the current technology for material bed systems[68] and electron based technologies[69] is that the production machines have to scale disproportionately larger than the volume of the geometry that can be created. *Potential Solution: Material fed process such as Laser Engineered Net Shape (LENS) are scalable and not constrained by size in terms of depositing build materials and placing a power source to process the powdered metal.*

4.4 Build Rate:

Build rate is major factor in determining the cost of producing a given component. Typical build rates for metal materials vary from 1.0 in^3 to 10 in^3 per hour; as a result, the build time for a typical component can be several hours if not days. While this is still faster than many conventional manufacturing approaches[70], it still increases AM manufacturing costs. The main

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[65] The initial layers of material are deposited on a cold build surface and have a different microstructure than the last layer that deposited on a much warmer surface. In addition, external corners and edges will see different cooling effect (microstructure) than internally filled portions of the component.

[66] This is not an easy effort; currently there is not a consensus on the parameters to be monitored. In addition, AM powder bed processes such as selective laser sintering typically scan their laser (or e-beam) at such a fast rate that a current process monitoring technology cannot control them in a timely manner.

[67] A CMM scan and / or probe is made *in situ* of the component. This approach is used on high tolerance applications like machining turbomachinery components.

[68] Selective laser sintering or stereolithography systems can require a machine volume up to 3X the build volume.

[69] Electron beam based technology requires a vacuum chamber to build the component in.

[70] When consideration for tooling, assembly and raw material procurement is taken into account

reasons why AM production systems were designed with these low build rates is that it allows for the production of finer detailed definition in the component. Therefore, any increase in the build rate will most likely result in coarsening of the feature detail that is produced. *Potential Solution: Increasing the laser (or electron beam) coverage area*[71] *will result in a faster melt time in both material fed and material bed systems. For the case of material fed systems, dithering or rastering the laser (or electron beam) can be used to increase the deposition rate and be turned off for building detailed features. Material bed systems typically raster the power source so the only course of action would be the application of a thicker layer or to speed up the powder solidification process.*

4.5 System Utilization Rate:

System utilization rate has not been identified by the AM community as an issue to address but it is a current economic issue that can only be resolved through technical development. The current cost of AM production machines coupled with limitations[72] on their utility makes their ownership prohibitive to a majority of the DLA industrial base. Also, the fact that a metal machine cannot process polymers and a polymer machine cannot process metal further reduces the utilization rate. As a result, the purchase of an AM production system can be risky for a Tier three (3) OEM. Recently, machine tool companies such as DMG Mori[73] have introduced hybrid CNC milling – AM production systems. By combining the ability to AM via a powder deposition process[74] and perform conventional CNC milling in the same machine utilization of the system will be increased. *Solution: One area that has yet to be addressed is the ability to have an AM production system that can utilize both polymers and metals. Development of an approach to address this could be useful for application in forward deployment situations where space and transportability are critical.*

Figure 8: DMG Mori Lasertec 65

4.6 Advanced Material Systems:

The development of new material systems is not a major factor in sustainment and maintenance applications but it is a consideration when AM is used to produce new production designs in future systems and thus needs to be accounted for in any holistic AM technology development effort. The minimum threshold requirement should be the achievement of mechanical properties of metals and polymer that are consistent with conventionally produced

[71] This will require increasing the power level to maintain an area power density.
[72] Repeatability of mechanical properties and geometric definition
[73] DMG Mori Lasertec 65, unit cost is estimated at $2M.
[74] Similar to Laser Engineered Net Shape.

materials[75]. However, the goal should be to obtain mechanical properties comparable to fiber reinforced composites[76] on a specific property basis. Failure to achieve this may require a choice in future designs between the use of composites that provide a weight reduction at a higher cost or the use of AM that provides a lower cost but with a system performance penalty. Unfortunately, AM does not lend itself to the use of continuous long fibers. It is these long fibers that give fiber matrix composites their higher mechanical properties. *Potential Solution: Use of nano or micro sized particulates as strengthening materials in the metal or polymer matrix*[77].

4.7 Design and Analysis for AM: Design and analysis for AM is not a major concern for sustainment and maintenance application as the form, fit and function is already established. However, one of the greatest opportunities that AM provides to the design of new production components is the ability to produce virtually any shape or design imaginable. With that design freedom is the difficulty associated with analyzing extremely complex geometry. As a result, there are new software tools[78] that use finite element based optimization algorithms to create complex shape that they are producible only by using AM, such as ligamented structures. However, these designs are not practical because they are not repairable and thus not sustainable and maintainable in the field. *Solution: Work with the software companies that are developing to establish design guidelines for sustainability and maintenance and critical flaw analysis that can be incorporated into their software.*

5.0 Summary and Recommendations

Dwindling Department of Defense (DOD) budgets, sequestration demands, and tremendous oversight on expenditures **make it** extremely **challenging** for the **services to maintain the high mission readiness and system availability (A_0)** required for increased operations tempo. The financial reality of doing more with less demands lower costs, faster turn times, and higher productivity. **Additive Manufacturing** (AM) has the potential to **revolutionize the way the military services achieve mission readiness** through sustainment and maintenance of DOD systems. However, this is going to **require a committed and sustained effort by the DOD agencies involved**. **AM technology,** in its **current state, can make meaningful** but limited **contribution in reducing the time and cost** to produce sustainment and maintenance items such as non-safety critical parts and tooling. However, if a **focused and holistic development effort that addresses policies, procedures and AM technology is conducted**, the time for AM to **realize its full potential** can be greatly reduced.

[75] Wrought properties in metals and injection molded properties for polymers.
[76] Such as carbon fiber and epoxy polymer matrix composites.
[77] Strengthen mechanisms could include load transfer, grain refinement, crack and dislocation propagation impairment.
[78] Such as Materialize or packaged in CAD systems by Parametric Technologies and AutoDesk.

Required for Success

- Establish a DOD level Policy that drives a streamlined approval process based on the current technical maturity and benefit
- Identify applications such as O-rings and gaskets (injection molding tooling), plastic parts such as knobs, dials and housings (Fused Deposition Modeling), and repair items where AM can have an immediate impact.
- Establish a cross functional, inter agency DOD working group that address the areas of: AM component identification, creation of technical data package and ESA approval.
- Significant investment in the development of persistent and *in situ* AM process monitoring technologies. Follow on with closed loop process control.
- Capture DOD best practices and establish a database.

Policy and Procedure

- Immediate deployment of AM on non-critical parts and tooling to gain experience and lessons learned.
- Pursue balanced and diverse applications to focus development efforts on including tooling, repair, secondary components and critical components.
- DOD policy to address issues related to ownership of the Technical Data Package.
- Establish a DOD standard for Technical Data Packages that defines requirements for geometry definition, manufacturing instructions and requirements, component use case and duty cycle and supporting engineering analysis.
- Address health and safety issues associated with powdered metal. Coordinate with technology development activities.
- Address and fund the establishment of a skilled workforce in key technical areas such as: Reverse engineering, CAD modeling, AM equipment programmers and operators and post processing and inspection.

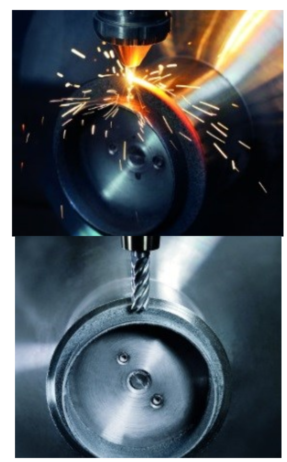

Figure 9: Example of a Hybrid CNC- LENS AM process to perform repairs

Technology

- Creation of a Digital Thread to capture design definition, design history and requirements, and support engineering approval.
- Holistic development a manufacturing process approach that addresses quality, economic, and safety concerns. Account for the impact of design & analysis and materials.

- Development of design allowables (A-basis / B- basis) consistent with Mil-Hnbk-17 (composites) methodology based on materials composition and processing conditions.[79]

Economics

- Holistic development of technologies, policies and procedures that enables the use of AM by tier 3 OEMs coupled with the military services logistics and maintenance infrastructure at the lowest cost of total ownership.

Execution of the aforementioned recommendations will be a **significant undertaking** in terms of time and cost, but **will result in** the **Warfighter being equipped with the most capable assets in the most affordable and timely manner as possible**.

[79] Such as melt pool size, temperature, cooling rate, etc

About the Authors:

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Mr. Herman has over fifteen years of combined experience working in the areas of additive manufacturing and nanotechnology. In 1997, he began his investigative effort in to carbon nanotube metal matrix composites for use in additive manufacturing during his tenure at Lockheed Martin. He has also contributed to and led additive manufacturing efforts at General Electric and CDI Aerospace. For these efforts, Mr. Herman has been awarded five patents. Currently, Mr. Herman is the manager of the engineering and technical services group at SHEPRA, Inc. and provides consulting on additive manufacturing to multiple DOD organizations and is currently the program manager on SHEPRA's efforts to develop next generation metal matrix composites for AM.

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Mr. Macy started in the digital thread and polymer Additive Manufacturing as a senior project engineer in the 1980s at McDonnel Douglas (now Boeing). From their Mr. Macy started a consulting business that helps SME's and DoD adopt digital solutions. His company assisted Stratasys in the development of their Direct Digital Manufacturing (DDM) group. More recently, Mr. Macy was appointed as the first deputy director of technology transfer for AmericaMakes. Currently Mr. Macy is assisting a number of clients ranging from private aircraft MRO service providers to SBIR Programs to AM equipment and sensor manufactures. These efforts include the development and demonstration of variety of tooling applications to repair and replace a variety of aircraft components.

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Mr. Stanley is the owner of Stanley Strategic Services and provides expertise in the areas of acquisition, logistics, depot maintenance, manufacturing, and enterprise IT systems. He retired as a USAF Senior Executive and his last position was the Deputy Director of Logistics, Office of the Deputy Chief of Staff for Logistics, Installations and Mission Support, Headquarters U.S. Air Force, Washington, D.C. During his career, Mr. Stanley was also the Senior Executive leading the Warner Robins Air Logistics Center Maintenance Wing, as well as the Vice Director of the Fighter/Bomber Aerospace Systems Wing at the Aerospace Systems Center Wright Patterson AFB Ohio. He currently supports the Air Force Research Lab in the area of Rapid and Additive manufacturing.

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Jason Ray is the Managing Director of JT Ray & Associates. He has demonstrated expertise in operations management, supply chain logistics and contract negotiation. He has extensive experience in aerospace acquisition and additive manufacturing from his time in the United States Navy. From 2009-2015, Jason served as an active duty Supply and Logistics Officer. He helped lead additive manufacturing implementation efforts, negotiated over $1B of innovation research and missile procurement contracts, and demonstrated effective leadership managing teams of 90 sailors on multiple Persian Gulf deployments. He has an MBA from Babson College, F. W. Olin Graduate School of Business and BA from Trinity College in Hartford, CT

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