Implementing Additive Manufacturing Technology Into the Logistics Supply Chain

Patrick Malone
MCR, LLC
550 Continental, Ste 185
El Segundo, CA 90245
310-640-0005
pmalone@mcri.com

Bruce Fad
PRICE Systems, LLC
17000 Commerce Parkway, Ste A
Mt. Laurel, NJ 08054
856-608-7217
Bruce.Fad@PRICESystems.com

Abstract— **Recent explosive growth in Additive Manufacturing (AM) or 3D printing is providing logistics supply chain economic opportunities. We investigate self-sufficient repair and maintenance capabilities for isolated environments, impacts on strategic readiness, increasing responsiveness and cost efficiencies not available in traditional supply chains. Our research will evaluate and contrast legacy logistics architectures against AM elements that will drive cost downward over lifecycles to meet current and future affordability goals within the Government and commercial organizations.**

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1. INTRODUCTION

Logistics Supply Chains- Now and Future

Logistics supply chains (LSC) exist in all organizations. The Aerospace and Defense industries have large and often complex LSCs that require significant management, forecasting and sourcing elements to sustain products and fleets. For example, the Defense Logistics Agency (DLA) procures and manages large supplies of spare parts to keep military equipment operating and ready.[1]

Commercial and defense industry contractors have similar LSC structures to maintain their products. In some cases they feed the DLA based on reliability, availability and maintainability (RAM) forecasts and actual performance.

LSCs like these are expensive and sometimes burdensome to maintain; so much so, the Department of Defense (DoD) has initiated efforts to reduce the LSC footprint across all services.[2] Moreover, because of acquisition reform and Better Buying Power (BBP) initiatives[3], reduced weapon system procurements and other factors, the United States (US) is faced with Diminished Manufacturing Sources and Materials Shortages (DMSMS) for critical technologies, out of production parts and counterfeit products that require innovative approaches to meeting RAM requirements for these systems.[4]

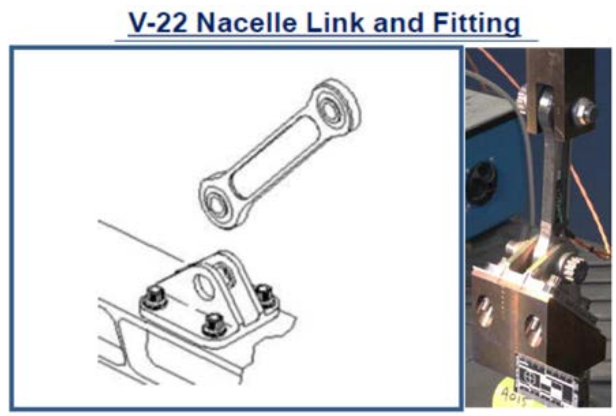

Figure 1 - AM produced safety critical component for V-22, fleet active in 2016.

Future LSCs will likely include additive manufacturing (AM), early warning counterfeit detection, Lean principles[a] to enhance efficiency, smaller footprints and optimized forecasting to minimize inventory costs.

Additive Manufacturing – The Enabler

Additive manufacturing brings promise to the LSC for non-obsolete and obsolete parts for several reasons. 1) demand forecast errors are almost eliminated, 2) lead times can be reduced to meet mission objectives, 3) reduced energy consumption to generate parts are possible and 4) AM parts can provide enhanced performance over original equipment manufacturers (OEM) parts with current and emerging advanced materials.[5]

Aerospace and defense industries continue to see benefits and embrace AM for systems, subsystems and components. Future designs will be AM focused and support the LSC optimizing replenishment, lowering energy consumption, minimizing waste, providing agility in manufacturing and

[a] Lean Principles: Lean manufacturing or lean production, often simply "lean", is a systematic method for the elimination of waste ("Muda") within a manufacturing system. https://en.wikipedia.org/wiki/Lean_manufacturing

reducing life cycle costs while maintaining performance and readiness.[6]

For example, the V-22 Nacelle Link and Fitting shown in

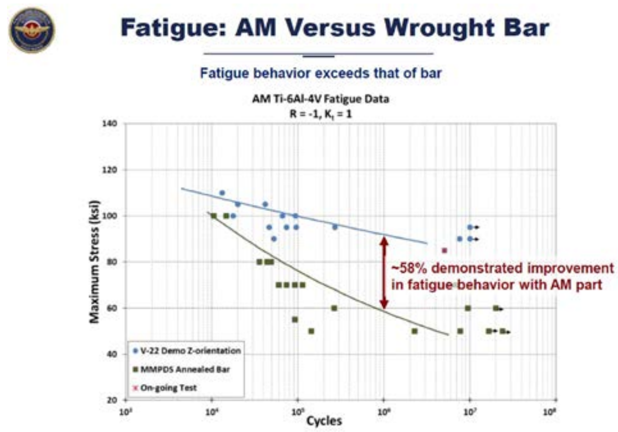

Figure 2 – AM Fatigue behavior exceeds that of titanium wrought bar (NAVAIR)

Figure 1 introduced to the fleet in 2016, as the AM replacement provides better fatigue life than the forged component it replaced. Qualified for life, it marks the first flight with AM produced safety critical parts. Twenty months from design start to first flight represents accelerated development of statistically significant data for airworthiness and 58% demonstrated fatigue improvement over the wrought titanium bar stock material it replaced as shown in Figure 2.[7]

Economic Opportunities

Opportunities abound as the technology advances. Imagine components, sub systems and possibly systems to implement AM in ways not seen before to support missions on demand, reduce costs and enhance performance.

AM technology maturity is growing at an exponential rate. Wohlers 2016 Report indicates the AM industry surpassed $5.1B demonstrating that interest and potential of the technology continues to be realized.[8] The result will be enhanced economic opportunities.

Cost Drivers

Today, for those components now being manufactured with AM, the top three manufacturing cost drivers are: 1) machine costs (73%), 2) material costs (12%) and 3) post processing costs.[9] While some traditional manufacturing organizations may balk, AM manufacturers can provide production quality customized parts in less time at competitive costs. This can result in embracing AM in future LSC architectures. Moreover, as new techniques, such as near formed materials become common, cost drivers are likely to change with this disruptive technology.

Future Research

Machinery's Handbook (MH) first edition was published in 1914. Now in the 30th edition as of March 2016, this guide for the "subtractive manufacturing" technology was, and still is the "Bible" of manufacturing[10]. As AM continues to grow in many industries, a "Ghost" AM-MH will emerge to guide AM technology for the next 100 years. We will continue to research and monitor the AM industry to support effective production, cost estimating methodologies and forecasting.

2. Logistics Supply Chains

Current Framework

Military, defense contractors, commercial manufacturing and, and sub-contractors have LSCs to conduct business operations. One of the largest is the United States Department of Defense's (DoD) DLA.

A typical LSC is comprised of eight elements shown in Figure 3. 1) A requirement or requisition generated based on need. 2) Receipt of the order to be filled by the supply agency. 3) Checking and pulling stock to fill the order is next. 4) Release of the stock for shipment. 5) Ship to the location needed. 6) Receipt by the requisition agency. 7) Restock action at the requisition agency. 8) Distribute to the requestor.

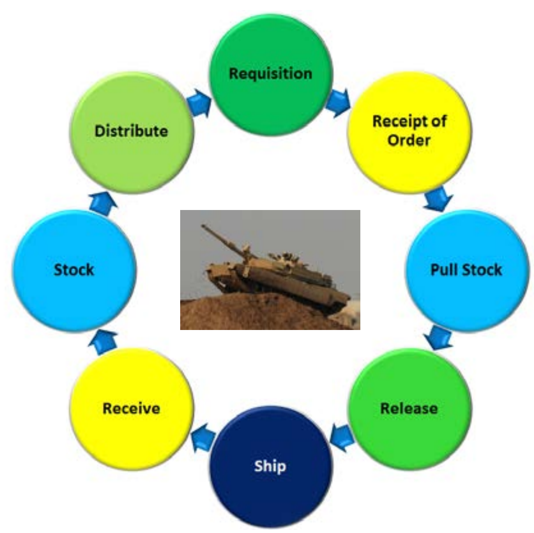

Figure 3 - Classical Logistics Supply Chain Process Flow

The DLA's motto is "*The Right Solution – On Time, Every Time*." Its headquarters is located at Fort Belvoir, Virginia with operating locations worldwide. The organization supports all five services; Army, Navy, Air Force, Marine Corps and Coast Guard. Their primary support activities span aviation, distribution, disposal services, energy, land and maritime and troop support. The main mission is establishment, management and operations of procurement policy and oversight for the DLA's 5.2 million line items that contain billions of part inventory. In 2017, annual sales were $35 Billion. DLA buys, stores and distributes equipment and weapons system repair parts, fuel, food, uniform apparel, pharmaceutical, medical and surgical products for the Military services and other Global customers.[11]

Commercial and defense industry contractors are applying knowledge from the Automotive industry supply chain to support efficiency and cost reduction in the growing competitive market.

For example, Aerospace OEMs are employing Lean principles such as Just-in-Time deliveries to their production and assembly lines, the Kanban[b] system for managing inventory, and point-of-use delivery for kits. Aerospace OEMs are also sourcing sub-systems rather than piece parts resulting in a reduction of suppliers and improving their supply chain efficiency. To help reduce costs through less raw material supply liability, there is a trend of OEMs implementing Vendor Managed Inventory (VMI), where suppliers own the inventory and are responsible for moves to the OEM.[12] This framework is fundamentally changing the supply chain equation and providing opportunities for new technologies such as AM.

Table 1 - Spares Metrics for Large Weapons

Weapon System	Weight (Tons)	Repair Parts per 1000 Miles Driven (Tons)	Repair Parts/ Weapon
M1A1 Main Battle Tank	60	13	21.7%
M1A2 Bradley Fighting Vehicle	32	1	3.1%
FCS (Forecast before Canceled)	20	2	10.0%

Issues and Shortcomings

Tracking and ensuring the DLAs 5.2 million line items are ready and available requires a large and complex infrastructure that covers a large footprint. To execute ordering, tracking and distribution, complex management and tracking systems are often used. These systems track and monitor current replenishment, inactive or obsolete inventory and potential counterfeit components. This environment has many pitfalls and can cause inefficiency and unforeseen expense. For example, the Army performed a study and found that a 60-Ton M1A1 Battle Tank required 13 Tons of spare parts per 1000 miles driven or 22% of the weight of the weapon system. Table 1 presents weapon system metrics for three similar products.[13]

In another study by RAND measuring replenishments based on forecast demand for an item with a unit price of $2,700 (BY 15) is illustrated in Figure 4 for a seven year period.[14] The data show how demand and inventory are tied together and the impact if demand is uncertain. In this case disposal of unused inventory resulted in a reduction of about 220 units of this one item totaling almost $600K. As is seen, with uncertain demand, there can be backorders or significant overstock items that will need disposal action and unnecessary costs. This clearly illustrates how AM can support uncertain demand to eliminate waste.

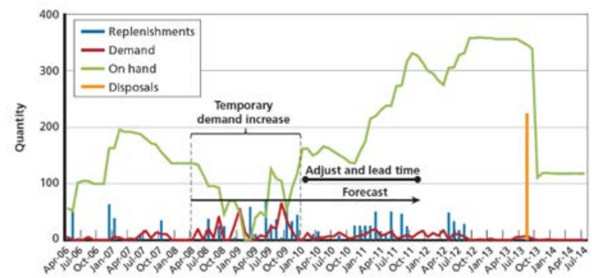

Figure 4 - Impact of uncertain demand to on-Hand inventory

Parts shortage is affecting US military readiness. So how big a readiness problem is it? The answer is certain to vary by service and system, but for one, the fighter/strike aircraft, it's very acute. On a given day, fewer than half of US Marine Corps F/A-18s, slightly more than half US Navy F/A-18s, and fewer than three-quarters of US Air Force fighters can fly with the rest grounded awaiting maintenance or spare parts. Figure 5 summarizes flyable aircraft by service. These numbers do not reflect those aircraft already in long-term depot maintenance. When those are added to the picture, Marine flyable inventory is a dismal 26% and the Navy a slightly better 39%: these are dangerously low readiness levels for critical weapons.

For the Navy F/A-18s, this readiness problem begins in the depot where maintainers wait for repair parts to arrive. In many cases, the same spare part is needed to repair multiple aircraft. It is realization of the inability of the supply chain being unable to keep up with demand and the compounding effect it has as deployed systems and utilization increase over time.[15]

U.S. Military Aircraft Readiness	
Flyable Aircraft Out of Aircraft Available to Units*	
Marine Corps F/A-18s (A-D)	42%
Navy F/A-18s (A-D and E/F	52%
Air Force Strike Fighters (A-10, F-15C-F, F-16C-D, F-22A, F-35A)	71%

Figure 5 – U.S. Military Flyable Aircraft by Service

[b] Kaban is a scheduling system for lean manufacturing and just-in-time manufacturing (JIT). Kanban is an inventory-control system to control the supply chain. Taiichi Ohno, an industrial engineer at Toyota, developed kanban to improve manufacturing efficiency.

For beyond LEO missions, NASA faces a similar readiness problem, better termed a capability problem. Weight has always been a premium with space flight. Anything that can be done to lighten the load is worth the investment for space systems. The International Space Station (ISS) carries 3 months of resupply inventory weighing approximately 13,000 kg (28,600 lbs). In addition, another 18,000 kg (39,600 lbs) of resupply sits on the ground ready on demand. That supply can be delivered in as little as one day. Not so for the Mars mission which requires capability to produce supply (including food) at the location where it is consumed. For much of the supply, 3D printing is the only way to meet the requirement.[16]

Government Accountability Office (GAO) analyses indicate that the average annual value of DLA's spare parts inventory for the 3 years reviewed (FY2006 – 2008) was about $13.7 billion (BY09). Of this total, about $7.1 billion (52 percent) was beyond the amount needed to meet its requirements objective, and this inventory represented 1.4 billion (55 percent) of the 2.5 billion parts that DLA held on average for each of the 3 years. They indicate accurate forecasting is the top root cause to obtain correct demand information. Their report (refer to Figure 4) found seven key factors contributing to mismatches between inventories[17]:

1. Accurately forecasting customer demands
2. Estimating lead-times for acquiring parts
3. Meeting the services' estimated additional requirements for spare parts
4. Improving communications among stakeholders to ensure purchase decisions are based on accurate and timely data
5. Modifying or canceling planned purchases of items that may no longer be needed to meet currently estimated requirements
6. Determining whether inventory being stored as contingency retention stock is still needed
7. Assessing and tracking the overall cost efficiency of its inventory management

An AM based model can mitigate many of these findings. For example, stocking generally applied materials and canceling planned purchases are cost and lead-time reduction opportunities, resulting in a just-in time delivery model. In another example, stored inventory reductions are realized due to generic broadly applied inventory materials.

Additive Manufacturing Opportunities

Another assessment performed by the RAND Corporation at the request of the Assistant Secretary of Defense for Logistics and Materiel Readiness, in coordination with DLA Logistics Operations and Acquisition found that key drivers in the LSC are lead-time and changing need for parts (accurate forecasting). The DLA, to support the warfighter effectively, must maintain adequate inventories of items for which demand is highly variable even when relatively stable, could increase or decrease dramatically on short notice, or may never even materialize. In fact, from 2005 to 2013, DLA disposed an average of more than $1 billion per year of products that were either obsolete, no longer needed. This resulted in LSC spending that was not needed. Unfortunately, the Department of Defense (DoD), considers this "cost of doing business"; the DLA charges its customers a mandated cost recovery surcharge added to material to cover its operating costs (which includes these disposal items).

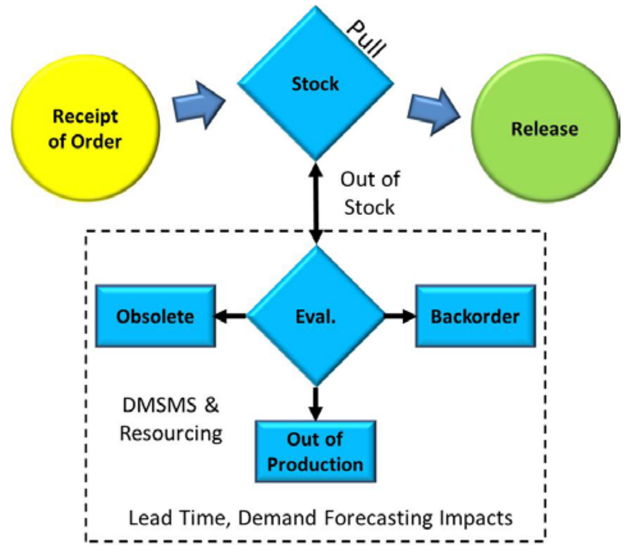

Figure 6 – Logistics Supply Chain process with out of Stock Items

Solving this problem is complex. DLA has to anticipate or forecast demand. The longer it takes to procure an item from a supplier (lead-time) the longer the horizon over which they need project the likely demand. Another factor is order size. The larger the order quantity relative to demand, the longer the time horizon over which DLA has to project demand (currently an outlook of 24 months). This lead-time uncertainty is prone with forecasting errors the further out it must go.[18]

In general, the typical LSC model shown in Figure 3 operates efficiently. However, if the demand is incorrect or changes unexpectedly, lead times and cost are impacted. Figure 6 illustrates some of the potential issues. In the simplest case, the item is back ordered. In other cases, the item may be out of production or worse, obsolete. This is where AM can provide an advantage in the LSC.

To reduce the risk of excess inventory and reduce unnecessary disposals and material costs, DLA needs to improve its supply chain agility says the RAND report. AM is a key enabler to mitigate this problem and improve the economic imbalance the current model creates. The AM supply chain agility (SCA) model can minimize obsolete or no longer needed inventory and address the DMSMS issues that they face by having a general set of materials and tools ready to create the needed items and deliver them on demand. The result will enable organizational efficiency and better customer service with the right stock, at the right time reducing demand and forecast error.

	AM Attributes compared to traditional manufacturing	Impact on product offerings	Impact on Logistics Supply Chains
1	Manufacturing of complex-design products	●	⊙
2	New products, break existing design and mfg limitations	●	⊙
3	Customization to customer requirements	●	⊙
4	Ease and flexibility of design iteration	⊙	◎
5	Part simplifications/sub-parts reduction	◎	◎
6	Reduced time to market	◎	◎
7	Waste minimization	◎	◎
8	Weight reduction	◎	○
9	Production near/at point of use	◎	●
10	On-demand manufacturing	○	●

Key:	Very High	High	Med	Low
	●	⊙	◎	○

Figure 7 – Impact of AM attributes on products and Logistics Supply Chain structures

While many organizations are in transition, the benefits of AM are many. The Quadrennial Technology Review of 2015[19] highlight seven:

- Innovation – designs with novel geometries, tailored material properties, etc.
- Part consolidation – design products with fewer, more complex parts
- Lower energy consumption – Save energy with fewer production steps
- Less waste – building layer by layer rather than "hog outs"
- Reduced time to market – Parts are fabricated as soon as design is complete
- Lightweighting – Same functional part with less material
- Agility of manufacturing operations – Less tooling, Manufacturing located at source of local materials, etc.

AM has numerous attributes that impact the LSC. Ten high impact items from the QTR shown in Figure 7 show the relative impact to product offerings and on LSCs.

Those working on and with AM technology strongly believe in the advantages offered to alter the landscape for military (and commercial) system maintenance. Cost and time savings in development and manufacture have already been established. By itself, these lower the sustainment cost portion of the life cycle.

Moreover, AM provides capability that has not been available before. Rapid digital design and manufacture enables untangling from the stranglehold of part obsolescence and scarcity/lack of source. As previously discussed, the DLAs 5.2 million line items, have an inventory of billions. Approximately 100+ parts have been identified as AM candidates that can reduce the current 5 million part inventory to 200, a scaling factor of 25,000:1 reduction! That's one potential payoff pushing the technology to readiness. All indications suggest the revolutionary nature of the opportunity is not overstated.[c]

3. Future Logistics Supply Chains

Future LSCs are evolving into fully integrated and optimized models. Economic optimization will include accurate forecasting techniques; ordering and stocking systems to anticipate varying demand, advanced manufacturing techniques to enhance material supply and smaller footprints that will meet affordability and warfighter needs.

A recent Aviation Week and Space Technology (AWST) article states *"The aerospace manufacturing landscape is undergoing a massive collective shift toward seamless integration of the digital and physical worlds, with the ultimate goal of interconnecting every process essential to the production of aircraft and other aviation platforms."*[20]

Known by a myriad of names; this Factory of the Future (FoF) will transform industries with new, more vertically integrated business process frameworks supporting efficiency and readiness. This shift is also necessary for competitiveness. For example, Airbus personnel state *"…production rates are already very high….as they continue to increase [they] reflect the doubling of global air traffic every 15 years, our production system needs to have the capability for this growth."*[21] They further, state to keep up with rise in output, factories cannot just add size to meet this demand; their reorganization will be a paradigm shift to leaner, agile and a digitally connected environment with smart and efficient technologies. The result will be efficient, competitive and cost effective products implementing effective technologies. AM is one of those technologies. Boeing is using AM extensively in production parts. The company has about 50,000 AM components currently flying on satellites and both commercial and military aircraft.[22]

[c] RADM Vince Griffith, Defense Logistics Agency discussion at the Additive Manufacturing Summit, Tampa, FL, 7 – 8 February 2017.

Figure 8 – NASAs AM Quality Standard

FoF will continue to mature, so will standards and security. For AM to become the "game changer," Government and military qualification standards for AM components and embedded cyber-security threat protection for digital designs are required. AM standardization and quality assurance is not simple to meet. System architectures will need to incorporate these attributes for AM to be reliable. Some segments, such as space, are further along than others in meeting the standards challenge. NASA, for example, drafted an AM Qualification and Certification Standard in July 2015 with a final release in 2017 so that AM parts can begin to fly and enable beyond Low-Earth Orbit (LEO) mission objectives to be met by 2018 (Figure 8). Beyond LEO missions, like that to Mars, are only possible with AM. Properly applying AM to space systems requires careful consideration; not all components are good candidates for the process; limited scalability is one reason.[23]

In NASA's journey to Mars and other deep space missions, AM presents a disruptive opportunity that aligns well with current and future missions. It can provide new materials and hardware as well as dramatically reduce costs and schedules to meet, perhaps exceed affordability goals. Their, in-space Manufacturing Initiative is developing the on-demand manufacturing capabilities required for sustainable exploration missions. Focus areas include new in-space polymers, multi-material fabrication, in-space verification and validation (V&V), and in-space design testing among others.[24]

$$Q = \sqrt{2k\lambda/hc}$$

$$Z = Q * (c + h) + k$$

Where:

- Q = Economic Ordering Quantity
- k = Purchase Request Cost
- λ = Annual Demand Rate
- h = Holding Rate (per dollar per year)
- c = Unit Purchase Cost
- Z = Total Annual Cost

Figure 9 – Economic Ordering Quantity and Annual Cost Model

The DLA LSC, now uses the "Economic Ordering Quantity" (EOQ) equation method. EOQ is the order quantity that minimizes total holding and ordering costs (typically for the year). In a RAND study by Peltz, et al[25] they discuss the value of EOQ, safety stock. However, when applying policy constraints, makes the EOQ approach suboptimal. They also indicate that without considering the relationship between order quantity and safety stock, EOQ techniques can be problematic and cause higher inventory (holding costs) and workload (impact of disposal costs). Figure 9 shows the classical EOQ and resulting total annual cost for quantity equations. Analysis of DLA data by RAND indicate the annual average Purchase Requisition (PR) cost for non-long term contracts (LTC) are about $440 (BY 08) per PR. Similarly, average annual holding cost for an item is 18% of the unit purchase price. The FoF can allow the EOQ to return to an optimized formula.

With billions of inventory components, optimizing the EOQ and safety stock can provide an efficient organization if demand is consistent. However, if historical demand is inconsistent or driven by external influences, then an AM model could support cost containment. Case in point, those working on and with AM technology strongly believe in the advantages offered to alter the landscape for military system maintenance. Cost and time savings in development and manufacture have already been demonstrated. By itself, lower sustainment cost portion of the life cycle has been realized. In addition, AM provides capability that has not been available before.

Figure 10 – The MV-22 Hydraulic Manifold AM manufactured in one piece from a legacy multi-part assembly

Additive Manufacturing has already demonstrated capability to significantly reduce component acquisition cost through both digital design and manufacture and combined by-products of reduced weight and reduced part count. Further, the performance and reliability of AM manufactured components are often superior to what is experienced with traditional reduction manufacturing and assembly, as the following examples illustrate. Consider the V-22 hydraulic manifold shown in Figure 10. This single piece product has a weight reduction of 70% over the legacy-manufactured 17-piece assembly that it replaced. The result is an item that significantly reduces failure rate with a conservative estimate of 240% reliability improvement. Previously we showed that AM techniques demonstrated an almost 60% improvement in reliability for the V-22 nacelle link and fitting without weight and part count reduction, both of which are likely to have a greater impact on reliability than AM alone.

4. ADDITIVE MANUFACTURING – AN ENABLER

Additive Manufacturing Theory

Additive manufacturing (AM) is a process of making a three-dimensional solid object of virtually any shape from a digital model using an additive process, where materials are applied in successive layers. AM is distinguished from traditional subtractive machining techniques that rely on the removal of material by methods such as cutting or milling.[26] There are many techniques in AM today, each provides unique attributes whether in plastic, metal or hybrid materials. The basic theory is the same, from a digital 3D model, material is built up in layers to form a solid 3D form.

Figure 11 – ARMDEC Aviation AM Repaired Part

State of the Technology

Today AM components are being used in some aerospace and defense environments for tooling, replacement parts and some flight-qualified applications. There is much room for growth. The LSC infrastructure is being readied for this disruptive technology but not fully in place.

The FoF continues to mature. Key to this maturity according to Deloitte Consulting is the digital thread for additive manufacturing (DTAM). It is defined as: "a single, seamless strand of data that stretches from the initial design concept to the finished part, constituting the information that enables the design, modeling, production, use, and monitoring of an individual manufactured part."[27]

The Office of Naval Research (ONR), Science & Technology focus is on cost reduction, increase in supply responsiveness, asset readiness, and combating part obsolescence.[28] While much work is required to be fully realized, incremental capabilities are being rolled out now that include: Polymer (plastic parts and tooling), Metal Spray, Repair, Depot-level metal capabilities to combat part obsolescence, and Expeditionary capabilities. Supported by the Department of the Navy (DON) AM Implementation Plan. This plan addresses the total life cycle in five areas:

- Integration of AM
- Quality and certification of AM
- Digital AM Framework
- Integrated Digital Grid
- AM Education and Training

As these areas are addressed, the Navy AM model will effectively and efficiently support the LSC.

The Army Aviation and Missile Research, Development and Engineering Center (ARMDEC) is doing much AM research. Reduction in part count and manufacturing steps for a gas turbine is one example reducing part count by 83% from 147 to 25 parts and eliminating 926 manufacturing process steps. In addition, high value components, those that fall under DMSMS or have long lead times are being repaired using AM. Figure 11 shows a worn and AM repaired seal. The result is increased system readiness and future LSC resiliency.

Future capability and the "tipping point"

A *tipping point* is the critical point in an evolving situation that leads to a new and irreversible development.[29] That is what AM is doing to industries. NASA's Space Technology Mission Directorate's (STMD) Robotic In-space Manufacturing and Assembly of Spacecraft and Space Structures has three tipping point projects

- Dragonfly: On-Orbit Robotic Installation and Reconfiguration of Large Solid RF Reflectors (Space Systems Loral)
- Robotic In-Space Manufacturing and Assembly of Spacecraft and Space Structures (Orbital ATK)
- In-Space Robotic Precision Manufacturing and Assembly (Made in Space, Inc.)

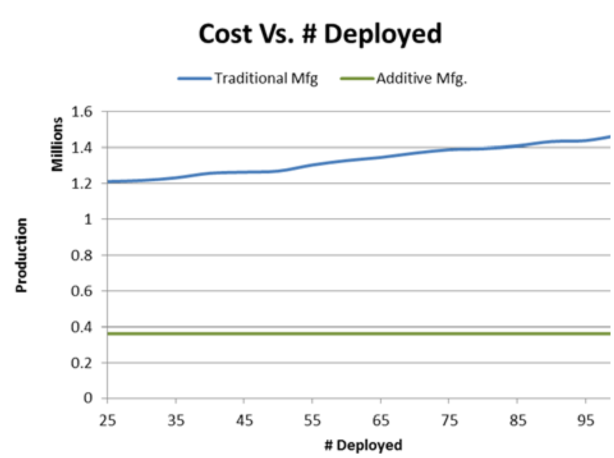

Figure 12 – AM Manifold realizes a 3:1 cost savings over traditional methods

These initiatives, with industry partnership, are pathfinders for influencing future long duration space missions and advancing the Technology Readiness Levels (TRLs) to make the AM environment viable in space.

Economic sensitivity (Cost modeling)

Maturing AM technologies are making an economic impact in many industries. LSCs worldwide see how they can capitalize on AM and Lean principles to minimize waste, increase efficiency and maintain enterprise competitiveness.

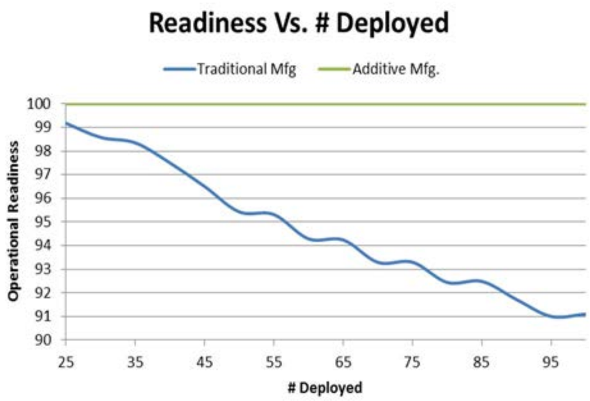

Figure 13 – Using AM methods Readiness can easily be maintained at or near 100% at minimal cost

Figure 12 illustrates the cost savings potential of AM. The 3:1 difference in production costs estimated for the manifold in Figure 10 is conservative when compared to reported savings by those working in the AM field. When operation and support phase is considered, there is an additional benefit to production costs by avoidance of the creep caused by added initial supply to fill the pipeline as deployed quantities increase. The AM capability to print on demand eliminates lead times; even with consideration of the significant cost of 3D printers, the saving is substantial.

The greatest savings opportunity by far occurs in the sustainment phase where differences in acquisition costs for spares, shipping, and maintenance labor are magnified. Operationally, and perhaps of greater importance to the user of a system is the difference between readiness potential of AM versus traditional manufacture. With AM, a constant readiness of almost 100% can be maintained regardless of the number of deployments. All it really takes is a printer and raw material at or near the using location to maintain a high rate of constant readiness. The graphic (Figure 13) clearly shows what is reported about many systems today; the struggle to maintain effective readiness in the face of increasing usage.

5. Cost Drivers in the Supply Chain

Beyond machine, material and post processing cost drivers for AM shown in section 1; there are two primary cost drivers in the LSC. They are uncertain demand and item lead times. In order for LSCs to maintain adequate readiness levels, they either need to have on-hand inventory or be able to quickly obtain it from a supplier. This was demonstrated in Figure 4 where uncertain demand drove inventory to minimal levels, then as orders were placed, inventory was maximized resulting in disposals. When lead times are long, the problem is exacerbated due to longer forecast periods. Figure 14 illustrates the impact AM can have on cost versus traditional methods for sustainment costs.

There will always be a level of uncertainty in demand. Significantly reducing lead times will drive LSC efficiency and reduce costs through minimizing inventory and holding costs. Future LSCs will be agile and integrate Lean principles, point of use manufacturing and other lead time reduction initiatives. As AM is fully integrated into new systems, infrastructure to leverage the technology will be more seamless. Holding cost will be minimized and lead time will be near zero making the future LSC perform optimally.

6. Future Research

It has been shown in this paper the advantages of integrating AM and 3D printing technologies into LSCs. The economic benefits will continue to grow as new systems integrate AM at the beginning of the lifecycle along with an ability to better forecast demand and reduce lead times to meet readiness objectives. Our research will periodically investigate the progress in these areas.

There is no doubt, AM is a disruptive technology. This applies to technology management as well as to its implementation. All aspects of management including cost modeling and estimating is different when compared to subtractive manufacturing. Our research has clearly identified some cost drivers of AM and suggested others. At this stage, we are left with two overarching implications of AM for cost estimators and modelers[30]:

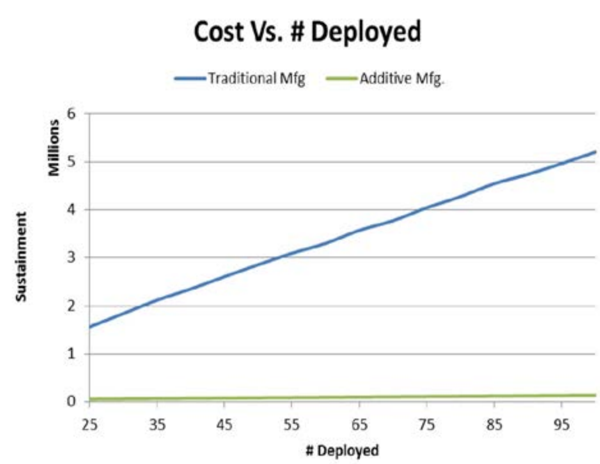

Figure 14 – Trade of AM versus Traditional sustainment costs for number deployed.

1. AM is capable of streamlining LSC, like the DLA 8-step system discussed earlier, to where cost and time of many steps practically disappear. There's no apparent reason why the 5 steps from, "Pull Stock," to, "Stock," cannot be replaced with the single step of, "Fulfill Order." AM enables it. In fact, a data driven approach to spares inventory management can maximize spares availability at a very low cost, making the LSC a simple 2-step process of, "Submit Requisition," and, "Receive Spare."

2. Beware the knee-jerk call for disposal of current methods/models for new creations of the AM world. It is certain that AM requires a different view of costing than that applied to subtractive manufacturing, but the end product is still created by engineering minds, raw materials, and hard and soft machinery. Some have suggested that there are no Cost-Estimating-Relationships (CERs) for AM. We suggest that the word, "yet," is missing from the statement and even that is stretching the truth a bit; some early models for AM manufacturing costs have already sprouted. Another published statement we take issue with is that complexity, which is a cost driver in some of today's models, is not pertinent to AM. We suppose that the claim pertains to the relative ease with which AM can achieve high dimensional tolerances and easily produce complex shapes. But, the scalability problem defined by the conflicting physics between 3-D build rate (material deposition rate) and feature definition (feature quality of end item) is a complexity issue that must be overcome before AM is a practical technology for anything roughly basketball size or larger. As with earlier technology advances like integrated circuits and Computer Aided Design (CAD), adaptation of existing costing methods by retaining and reshaping what works well and adding what to it that which is new seems to be the best track to follow in developing AM CERs and models.

7. Summary and Conclusion

Our discussion started with an overview of traditional and current LSC operations and issues. Then we introduced AM disruptive methods and showed how LSC improvements can be made through inventory reduction, cost efficiency and other factors. We showed how AM is being used for new and repair parts that will further enhance efficiency and reduce lead times.

All it really takes is a printer, raw material at or near the using location, and a quality assurance methodology to maintain a high rate of constant readiness.

Biography

Patrick Malone *Patrick Malone is a senior consultant at MCR, LLC. He has significant analytical and hands-on experience in the aerospace industry from ground to space systems. His current work includes cost estimating of UAVs and Space systems. He has written papers on Additive Manufacturing Technology Readiness Levels and System Readiness Levels to improve cost-estimating confidence. Mr. Malone is a Professional Engineer in California, holds a BS from Arizona State University and an MBA from Pepperdine.*

Bruce Fad *Bruce Fad is Senior Vice-President, PRICE Systems, LLC. He has worked in cost estimating for over 38 years as an estimator, tool provider, expert witness, researcher, and instructor. He was a junior officer in the US Army, an Operations Research analyst at NSA, and Acquisition Management manager at Lockheed. He holds bachelors and master's degrees in Math from University of Delaware. He is a contributor to recent PRICE tool additions to estimate Additive Manufacturing/3-D Printing.*

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