

AIR COMMAND AND STAFF COLLEGE

AIR UNIVERSITY

THE FUTURE OF ADDITIVE MANUFACTURING

IN

THE US MILITARY

by

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Abstract

Additive manufacturing – of which 3D printing is a subset – describes a manufacturing technique in which objects are built up from raw material one layer or three dimensional pixel at a time. Today materials from plastics to a small range of metals can be 3D printed, and the technology is growing rapidly as we write this paper. The DoD, as a large consumer of manufactured goods, is vulnerable to this technology while also being in a position to embrace this manufacturing wave of the future. As described in the Joint Operating Environment 2035, the world continues to grow more complex and uncertain, and this environment demands more agile and flexible capabilities from the DoD. Additive manufacturing will give the DoD manufacturing capabilities and supply chain advantages that will transform global operations, but it cannot achieve these breakthroughs without serious structural changes to current acquisitions and contracting policies and procedures.



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INTRODUCTION

Three-dimensional (3D) printing, also known as additive manufacturing (AM), is a relatively new technology that threatens to turn manufacturing on its head, just as inventions like the spinning jenny and cotton gin did in the past. The challenge in verifying the audacity of such a revolutionary claim is discerning history's lessons on technology, and making educated decisions and investments for the future. The Department of Defense (DoD) oversees a broad array of operations, and consumes an incredible amount of manufactured goods; therefore, when a technology like 3D printing comes along, it is imperative for the DoD to stay grounded in the education of manufacturing's technological history, while making bold investments into those technologies that may entirely change the game for the organization. The purpose of this research is to decipher the lessons of manufacturing's past and present history, and peek into the future to offer recommendations and answer, "What is the future of 3D printing for the military in the anticipated operating environment of 2035?"

Technology throughout history typically follows a pattern of making human endeavors easier, quicker, more reliable, and less costly. Manufacturing technology fully fits this description, and also has a reputation for eliminating human labor as well. Taking early advantage of manufacturing technologies creates large disruptions in the business world, the most vivid example of which was Henry Ford's assembly line. Harnessing new technologies has also helped create the most robust military the world has ever known right here in the United States. And, while there are many eye-catching technological advances touted today, perhaps none is quite as revolutionary as 3D printing. The identification of 3D printing as a potentially revolutionary technology is not complicated: any technology that seriously challenges the source

of goods and the origin of manufacturing needs to be taken seriously, and history will show this to be true.

TRANSFORMATIVE TECHNOLOGIES IN MANUFACTURING

For the bulk of history, manufacturing moved at a pace commensurate to the limitations of the human hand. Within the past 300 years, however, certain technological advancements and scientific breakthroughs have repeatedly pushed manufacturing forward into new and distinct eras. These technologies can be described as being transformative, in that they changed the very nature of the manufacturing enterprise.

The Origins of Manufacturing

Prior to the Industrial Revolution, manufacturing simply meant creating products or goods by hand.¹ Indeed, the Latin derivation of the word, “manu factum,” translates to “made by hand.” Such practices are representative of all societies throughout human history. In ancient Greece, for example, manufacturing was a family affair in which nearly every household took part. As the society on whole lacked any industrial machinery, most families were likely to produce their own materials, food, and clothing. Using basic tools, many of these households produced simple ceramics, carpentry, or metalwork for their personal use. When the household produced a surplus, they would look to exchange their goods with neighboring homes or farms or sell them at the market.² The largest enterprises of the time involved those requiring significant amounts of slave labor, such as a shield making; however, the success of these makers still depended on the quality of their craftsmanship.³

The Age of Artisans and Trade Guilds

In the centuries proceeding the Industrial Revolution, tradecraft by skilled artisans was the primary means of consumer good production. Aspiring craftsmen studied at unique trades

such as blacksmithing, rope making, or masonry under the tutelage of a master. Only through years of apprenticeship could an aspiring artisan learn the skills of the trade, obtain journeyman status, and ultimately gain the experience and certifications necessary to become a master craftsman. Much like the household-based manufacturing operations of antiquity, craftsmanship in the Middle Ages quite often remained a protected family business, passed on from one generation to the next.⁴

Seeking further protection of their particular tradecraft from outside influence, members of these manufacturing professions organized into various trade unions and associations, known commonly as guilds. Guilds ensured that certain skills, tools, and materials unique to a given tradecraft remained in the control of guild members, often enjoying the market protection of royal grants and patent letters. Historians have argued that the formation of such guilds hindered technological innovation and development, as their market control restricted free competition.⁵ By the 18th century, very little had fundamentally changed in the practice of manufacturing since ancient times—consumer goods were still made by human hands.

Enlightenment and the Industrial Revolution

The Age of Enlightenment represented a fundamental shift in the way western civilizations viewed and shaped their world. Beginning in the late 17th century, progressive minds began to consider revolutionary philosophical ideas such as individual liberties, social progress, and the scientific method. Understanding of the sciences grew during this period as publications like Newton's *Principia* and the collective works of the *Encyclopédie* spread across Europe.⁶ By the mid-18th century, innovators were applying the scientific advancements made in mathematics, physics, and chemistry to the development of machines that could help increase the

production of goods. The Industrial Revolution grew out of this rapid advancement of productivity improving technologies.

Earliest Transformative Technologies

By the mid-18th century innovative mechanical designs emerged that began to exploit the outputs of existing energy producing technologies such as the water wheel. These new mechanical designs reliably outpaced work done by hand, vastly increased production, and thereby ushered in the first major transformations to the manufacturing process.

Some of the earliest examples of these transformative technologies exist in the realm of textile manufacturing. At the start of the 18th century, the process of thread spinning limited the overall production capacity of the wool and cotton industries. At that time, it took at least four women working on separate spinning wheels to supply the demands of one weaver on a loom.⁷ James Hargreaves' hand-powered spinning jenny of 1764 allowed workers to spin multiple spools of thread at once. Subsequent transformations of the spinning jenny into the water-powered water frame and spinning mule meant that a single machine could simultaneously produce multiple spools of thread with substantially greater quality and strength than those produced by hand.⁸

These dramatic improvements in spinning technology spurred other mechanized innovations throughout the textile industry. By the late 18th century, Eli Whitney's cotton gin helped suppliers meet the increasing demand for raw materials, while multiple iterations of mechanical weavers consumed the growing output of thread.

Factories, Transformative Machining Technologies, and the Beginning of Mass Production

The advancements in spinning technology and the ultimate replacement of water wheels with steam engines ushered in the factory system of manufacturing. No longer the work of

individual households, manufacturing now took place in dedicated factories and employed laborers to run the machines of industry.

Integral to these factories were machine tools capable of rapid production. Across a wide range of industries, machine tools replaced the work of the craftsman by providing product uniformity and production speeds impossible to replicate by hand. Machine tools allowed industries to develop products like firearms based on a system of interchangeable parts. In 1798, Eli Whitney of earlier cotton gin fame was determined to “make the same parts of different guns, as the locks, for example, as much like each other as the successive impression of a copper-plate engraving.”⁹ Like many innovators, Whitney faced considerable skepticism to his ideas. Doubters mocked and ridiculed his concept, claiming that such a system would have enormous cost.¹⁰ Not without some difficulty, Whitney’s efforts to introduce interchangeability took several decades, but eventually became the standard for firearm production.¹¹

Across the Atlantic, engineers in Portsmouth, England were transforming rigging block production into a mechanized system based on interchangeable parts. The Portsmouth Block Mills made use of some 45 machine tools to produce over 100,000 blocks per year, using a mere tenth of the manpower that was required for manual production.¹² The increase in production met the demands of Lord Nelson’s expanding navy at the height of the Napoleonic Wars.¹³ With the later introduction of electrification and assembly line factory methods, machine tools made mass production possible.

Mass production grew more commonplace in the early 20th century. The Ford Motor Company popularized the concept of mass production by merging electrical conveyor systems with assembly line efficiencies and machine tool processes. Ford made use of roughly 32,000 machine tools throughout the streamlined assembly line process of the Model T,¹⁴ at times

producing a new car every three minutes.¹⁵ The factory infrastructure and mass production innovations established by Ford and other early 20th century industrialist enabled a scale of production that not only fundamentally transformed manufacturing, but also transformed the societies they served. The scale of mass production offered lower costs to the consumer, which meant that even the Ford factory workers could afford to buy a Model T on three months wages.¹⁶ By mid-century, the industrial base of the United States was capable of meeting wartime production demands for a world war fought across two theaters.

Computer Integrated Manufacturing, Industrial Robotics, and Computerized Control

The most recent transformative technologies to affect the manufacturing industry have developed out of the digital sector. Within the past 50 years, robotics and computer-aided processes have further automated the manufacturing world, reducing the hands-on role of people in the production of goods. Computer integrated manufacturing is now a well-established norm in all of the major industries including automotive, aviation, space, and shipbuilding.

Although the earliest patents for industrial robotics were filed in the 1950s, the industry did not see its first phase of rapid diffusion until the 1980s.¹⁷ Today, modern manufacturers use industrial robots for a variety of applications. Robotic arms are ideal for a wide range of repetitive processes previously accomplished by hand. Preprogramed robotic arms can accomplish a variety of repeated tasks such as welding, painting, packaging, and palletizing more efficiently than their humans counterparts. Likewise, automated storage retrieval systems and automated guided vehicles are further examples of manufacturers seeking production efficiencies by removing the human element.

Computer Numerical Control (CNC) milling is another example of how computers are automating processes previously controlled by hand. Not unlike industrial robotics, the earliest

CNC milling technologies emerged in the mid-20th century, yet demand for such technology did not develop until the mid-1970s, when slumping global economies drove machine tool users to seek efficiencies in production.¹⁸ A CNC milling machine uses computerized controls to cut a raw piece of material into a desired shape. The dimensions of the desired part are defined using computer-aided design (CAD) software. Computer-aided manufacturing (CAM) software then translates the specific CAD file into data that tells the CNC machine how to cut the particular part. The simplest CNC milling machines work on three planes, while more advanced machines offer rotation around one or more axis.

Analysis of Transformative Technologies in Manufacturing

The history of manufacturing indicates a recurring tendency in which transformative technologies replace a pre-existing norm. Initially, skilled craftsman were replaced by machines managed by unskilled laborers. Later, many of these unskilled laborers began to be replaced by computers and robots, further reducing the human element in the production of goods. The transitions were never immediate, as innovation tends to meet with resistance. History shows that when transformative technologies emerge, they generally take 20 to 50 years of development and implementation to have their full effect on industry.

Presently, however, the widespread availability and decreasing cost of computerized technology may bring manufacturing full circle, putting the process of production—from raw material to finished product—back into the hands of the creator. Economist Peter Acton suggests that the current dispersal of information on the internet is reversing the consolidating effects of the Industrial Revolution.¹⁹ Ease of design and production for the individual is shifting the cost advantage away from long-established manufacturing businesses.²⁰ While this technology remains far from ubiquitous, the time of artisans creating their own products – designed on

computers and produced on personal CNC milling machines or 3D printers – may not be far away. Given another 30 years, additive manufacturing may well be the next transformative technology in manufacturing.

A HISTORY OF ADDITIVE MANUFACTURING/3D PRINTING

The history and growth patterns of technology can help educate its future outlook. Additive manufacturing is roughly 36 years old, and although it sputtered at first, it has grown rapidly over the last 20 years. The first 3D printing attempts are credited to Dr. Hideo Kodama for his development of a rapid prototyping technique in 1981. He was the first to describe a layer-by-layer approach to manufacturing, using photopolymers to build a 3D object.²¹ In 1984, Charles Hull took this technology a step further, inventing the stereolithography apparatus (SLA), a printing process that enables a tangible 3D object to be created from digital data. The technology wasn't perfect at first, but its potential was undeniable, allowing users to test a design before investing in a larger manufacturing program.²² Within the next decade, inventors also created the first selective laser sintering (SLS) machine for printing metals, as well as the first fused deposition modelling (FDM) machine. Within ten years, the three main technologies – SLA, SLS, and FDM – of 3D printing were born.²³

The first SLA machine, produced by 3D Systems in 1992, used a UV laser to solidify photopolymer. Essentially, it's taking a liquid with the viscosity and color of honey and turning it into three-dimensional parts layer by layer, creating highly complex parts that can be manufactured overnight.²⁴ Since that time, other technologies have added to 3D printing's usefulness, such as the first multicolor 3D printer built in 2000 by Z Corp.²⁵ The table below gives a brief side-by-side comparison of SLA technology over the last decade:

	1996	2016
Price – Top of the line SLA 3D Printer?	Approx. \$585k USD	Approx. \$735k USD
Build Speed – How long to ‘full build’ a block on the printer’s platform?	10 Days	2-3 Days
Setup Time – Man hours.	6-8 hours PLUS an overnight slicing procedure on the Silicon Graphics workstation.	Less than one hour.
Running Costs – Laser cost and lifetime.	\$39,000 USD per laser 2000 hour lifespan	\$61,000 USD per solid state laser 15000 hour lifespan
Material Choice and properties	SL 5180 standard resin Slow to build, brittle when handled, and it would grow in size by 2% as it absorbed moisture from the air	Multiple filled/flexible resins, ABS, PP simulants, etc. Fast build, strong and no moisture effect
Typical Part Cost	Example: a large automotive glove box molding taking up half a platform at approximately 300mm tall was roughly \$6,000 USD	The same component would be approximately 75% less, \$1,500 USD

Table 1: SLA Comparison²⁶

One of the largest and most successful growth sectors for additive manufacturing is in the medical industry. Today human body parts like the brain can be replicated using the 3D printing, aiding complex surgeries through simulation.²⁷ In 2008, 3D printing achieved great media presence thanks to the first 3D printed prosthetic limb.²⁸ It incorporated all parts of a biological limb, and was printed ‘as is’, without the need for any later assembly. Nowadays, combined with 3D scanning, medical prosthesis and orthosis are better and cheaper and extremely fast to obtain. Walter Reed Army Medical Center has created and successfully implanted over 60 titanium cranial plates, and in June 2011 the first 3D–printed jaw, also made of titanium, was successfully implanted in an 83-year-old woman by Dr. Jules Poukens of Hasselt University.²⁹ Perfectly matching implants to a patient’s body provides better fixation and reduces surgery time and infection.³⁰

The quest to print living tissue, commonly known as bioprinting, is opening up new avenues for regenerative medicine. With improved understanding, researchers hope to catalyze the natural healing mechanisms of the body by creating porous structures that aid in bone

stabilization in the field of orthopedics.³¹ This technology, in conjunction with stem cell research, could eliminate transplant waiting lists. Research at the Wake Forest Institute for Regenerative Medicine aims to print entire organs and tissues using 3D printing technology.³² And, while we will likely have to wait years to see printed organs transplanted into a patient, 3D printed kidneys are now functioning perfectly in laboratories. Bioprinting is a very real application that has grown tremendously over the last couple decades, pushing the field of 3D printing into the future.

In 2004 another big idea in the industry came by way of the RepRap Project, which consisted of a self-replicating 3D printer.³³ This open source project led to widespread interest in home use FDM 3D printers, and found popularity in what is commonly referred to as the ‘makers’ community. In 2009, FDM patents fell into the public domain, opening the way to a wide wave of innovation in FDM 3D printers. Since that time, the price of 3D printers has dropped significantly, consequently giving the technology more visibility and accessibility. In 2009, the pioneering concept of on-demand online 3D printing services came to the mainstream with Sculpteo, a company that continues to flourish and grow today.³⁴ All of these concepts came together within the last 15 years, and it reveals significant growth by way of allowing end-users to explore the technology of 3D printing, which is a potential lesson that could yield excellent results for the DoD.

Some of the most involved and visible applications throughout the history of additive manufacturing are in the aerospace and automotive industries. Both were early adopters of the technology, and have been designing small to large 3D printed parts that save time, material and costs. Engineers at the University of Southampton designed and flew the world’s first 3D-printed aircraft – the unmanned aircraft was built in seven days for a budget of \$6,000. 3D printing

allows the plane to be built with complex elliptical wings, a normally expensive feature that helps improve aerodynamic efficiency and minimizes induced drag.³⁵



Figure 1: 3D Printed: Southampton's Aircraft and Local Motors' Strati^{36,37}

Among the numerous companies using 3-D printing to ramp up production are GE (engines), Lockheed Martin and Boeing (aerospace and defense), and Aurora Flight Sciences (unmanned aerial vehicles). For the automotive industry, 3D printing technology presents challenges and opportunities alike. Automotive application has come from simple 3D printed fasteners a decade ago to entire cars such as Local Motors' "Strati" today.³⁸

The finances of 3D printing have changed drastically as well. As the Consumer Electronics Association noted, "Sales of 3D printers will approach \$5 billion in 2017, up from \$1.7 billion in 2011, as demand expands for everything from consumer applications to markets such as automotive, aerospace, industrial and healthcare."³⁹ In 2014, sales of industrial-grade 3-D printers in the United States were already one-third the volume of industrial automation and robotic sales and some projections have that figure rising to 42% by 2020.⁴⁰ If these numbers are indicative of what's to come, 3D printing will soon dominate the global manufacturing market for functional parts, fit and finish components, and molds and tooling for heavy duty equipment and machinery.⁴¹

THE CURRENT STATE OF 3D PRINTING

Additive manufacturing is growing and maturing at incredible rates, which makes adoption by a large entity such as the DoD difficult. As an organization, the DoD leans toward proven technologies and equipment that is thoroughly tested. While AM holds vast potential, there is difficulty in back-testing and reinventing manufacturing processes after certain techniques have already been approved, especially in high-cost industries like aerospace and defense. Despite these difficulties, the DoD needs to start somewhere, and answering two questions regarding the current state of AM will help: one, where is AM technology at today; and two, what can it do for me now?

Rumors of the magic of 3D printing are vast. From cars to houses, there are companies advertising 3D printing panaceas far and wide.^{42,43} Separating hype from fact isn't easy because today's hype might be tomorrow's fact. But it would be foolish for the DoD to march to war with completely unproven technology, so there has to be some sense of reality in today's expectations, as well as reliability in equipment and processes. Using a few examples, the ensuing discussion will focus on parsing the hype, giving the DoD reasonable expectations from which to begin adopting AM for the warfighter.

A Snapshot of Present-Day AM in Aerospace and Defense

United Launch Alliance (ULA) sits atop what may be considered the pinnacle of the aerospace industry – space launch. They are the primary contractor for the USAF launch enterprise. A few of the common descriptions associated with the space industry include exacting standards, precise manufacturing, exotic materials, and high cost, high quality results. If any organization could verify the efficacy of additive manufacturing (AM), it would be ULA. Unfortunately, and much to this research team's surprise, ULA uses very little AM today. Aside

from small brackets, access panels, and a camera lens cover, ULA has not adopted AM in a ‘game-changing’ way. Instead, ULA uses a methodical approach in deciding where to use AM, and has integrated AM in small but useful areas where traditional manufacturing is limited.

ULA runs into the same problem as the DoD in adapting AM technology to the aerospace industry: the demanding standards and certification of the vehicles, planes, rockets, and their manufacturing techniques are a huge roadblock to adopting AM in rapid fashion. In ULA’s case, they have an entire team of engineers dedicated to researching and calculating where AM makes sense from both an engineering and financial aspect.⁴⁴ In the end, the demanding environment of space launch – to include extreme hot and cold temperatures, vibration, and drastic atmospheric changes – adds up to limited practical application of AM for now. In fact, the ULA launch vehicle assembly facility in Decatur, AL, houses only one 3D printer, limited to two materials: ultem and ABS.⁴⁵ Both materials are advanced as far as ‘plastic’ goes, but their capability is still a far cry from being able to ‘print’ a rocket. The realities of space flight and the manufacturing certifications inherent therein stymie rapid changes in materials and manufacturing techniques, and ULA’s lack of massive AM integration in their current rocket assemblies reveal the limits of such technologies.

ULA is taking a methodical approach to AM, and their current model is worth understanding as it relates to 3D printing capabilities today. Given the complexities in space launch, ULA chooses to focus their efforts on three areas, in the following order: tooling, rapid prototyping, and polymer/metallic flight hardware.⁴⁶ Tooling is first because it is typically cost-effective to 3D print tooling jigs, templates, etc. due to their complex shapes and low volume. Traditional manufacturing is limited in both of these areas, and ULA takes advantage of their in-house capability to bypass costly manufacturing of unique tooling requirements. Second, rapid

prototyping using AM enables ULA to perform R&D type events early in the manufacturing process at lower costs. The following graphic explains the difference in AM rapid prototyping vs. traditional manufacturing processes:

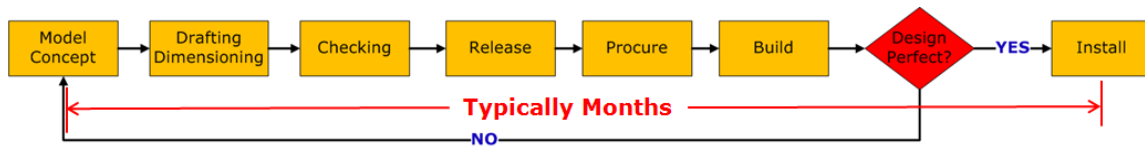


Figure 2: Traditional Engineering Process Flow⁴⁷

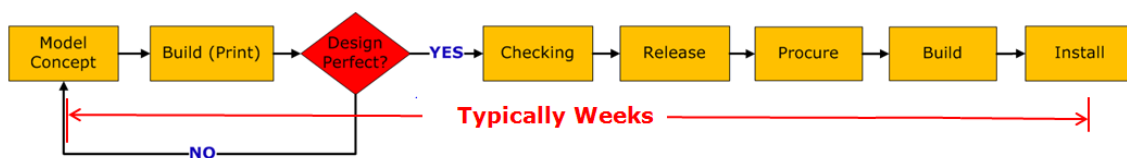


Figure 3: Engineering Process Flow Using Rapid Prototyping⁴⁸

Finally, ULA has focused much effort in manufacturing flight hardware using AM technology; however, the process is lengthy and has yet to live up to the hype. For example, their efforts to certify one material, ultem, took six months and started from a pool of 150 different materials.⁴⁹ And, despite all the time and effort, the material still carries significant restrictions on its application, which pigeonholes its use to temperature-limited, non-load critical parts. The takeaway from ULAs efforts is simple: AM is useful and promising, but we have only seen the tip of the iceberg at present, and it is not going to replace traditional manufacturing methods any time soon.

Understanding how to think about AM today is just as critical as the technology itself. First, it is important to understand that AM is not a panacea; instead, its biggest strength is in supplementing other manufacturing methods.⁵⁰ AM fills a role in the manufacturing process, and its niche is in low-volume, high complexity parts:

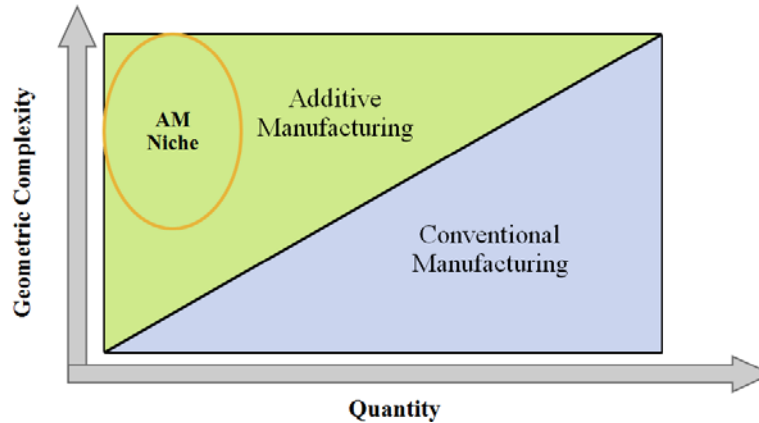


Figure 4: Additive Manufacturing's Niche⁵¹

If the DoD wishes to implement AM technology today, which is encouraged, then understanding Figure 3 is of great benefit in allowing the technology to properly mature into the future. The DoD should seek to find and apply AM to those enterprises that fit its ideal niche. Doing so will save time and money, as well as smartly gaining useful AM products while gathering innovative ideas along the way.

What AM Can do at Present

While space lift may not be ideally suited for rapid implementation of AM, knowing what capabilities are on the market today can certainly open innovative doors for the DoD in many other areas. For example, a leading company in the 3D printing business today is Stratasys. They have the capability of printing 82 different plastics, as well as 8 different metals, including stainless steel, titanium, and aluminum.⁵² Although their data would most certainly have to be verified by the DoD, the table below shows a snapshot comparison of typical metal properties vs. the claimed properties of the similar 3D printed material:

Material	Ultimate Tensile Strength	Yield Strength	Elongation at Break	Hardness
Aluminum 6061-T6 ⁵³	45 ksi	40 ksi	12-17%	60 Rockwell B
3D Printed Aluminum ⁵⁴ (AlSi 10 mg)	41-55 ksi	32-34 ksi	6.9-14.1%	64 Rockwell B

Table 2: Comparative Properties of Aluminum (Traditional vs. 3D)

What the table shows is that claimed properties are in line with traditionally manufactured materials. The broader point is that there's little reason to avoid entry into the AM field. The DoD is in a unique position to have both operational test units and research and development organizations for more complex projects, and it could take immediate measures to field this technology.

As material science progresses and more tests are concluded, AM will find new uses. But for now, snapshots of AM's abilities across several industries can help guide the DoD as to where best it should spend time and money with AM. In the aircraft industry, AM is steadily taking over manufacturing duties for complex parts that historically require manufacturing several pieces separately, then assembling those pieces later in the process. For example, CFM International (a joint GE Aviation and Safran venture) is manufacturing its newest LEAP engine using AM to 3D print the fuel nozzles – consolidating 20 subcomponents into a single build, creating a part that is 25% lighter and five times more durable than it's conventionally manufactured predecessor.^{55,56}

Likewise, the US Navy's Fleet Readiness Center Southeast used the advantages of AM to design an hydraulic intake manifold for the V-22 Osprey, meeting the challenge of complex design and unique material properties in grand fashion: they created a solution that is 70 percent lighter with improved flow and fewer leak points than the part which it replaced.⁵⁷ These aviation-centric examples further the aforementioned narrative that AM is ideal for complex, low

volume parts, and its strengths are best exploited alongside traditional manufacturing methods to create both time and money saving processes, as well as building better parts. In this sense, AM has very distinct advantages in addressing the aging fleets and obsolete hardware the DoD is notorious for maintaining. Current AM capabilities could be employed immediately to spur innovation across the enterprise in this area.

In other areas, AM technology is ready for an organization like the DoD to give it a home today. For example, there are several companies boasting the ability to 3D print vehicles.⁵⁸ Given the large vehicle fleets the DoD maintains, this is an area ripe for disruption. Another advantage of starting with projects like vehicles is that the DoD can test things safely here in the US without having to put soldiers in harms way with unproven technology. Figuring out which AM parts and materials are best suited in standard vehicles – before fitting them onto warfighting vehicles – carries with it significant savings and research potential.

Similarly, Hewlett Packard's newest 3D printing technology boasts the ability to print high strength parts with built-in stress sensors. They successfully printed and tested a high-strength composite chain link that weighs $\frac{1}{4}$ pound and can handle loads of 10,000 pounds.⁵⁹ The link took 30 minutes to print, and HP says their ability to imbed strain-gauge arrays (Wheatstone Bridges) allows the user to actively monitor stress in the part.⁶⁰

With present-day technologies like this, there's virtually unlimited potential to field operational research across the vast array of areas the DoD encompasses. At present, AM technology is mature enough to field under the right circumstances. Additionally, the cost of a commercial machine today is around \$100k to \$500k, depending on the capability, which is well within the budgets of bigger DoD organizations. How the DoD wishes to go about monitoring the AM enterprise will be discussed later, but the takeaway is that there is enough mature AM

technology on the table now to start seriously executing operational research and implementation.

SNAPSHOT: The Future of AM in the US Air Force

The low-volume, high technology environment of the US Air Force is ideally suited for adapting AM. From air base defense to battle damage repair, there are areas over the coming decades that can benefit greatly from AM. Imagine the following future scenario, circa 2035:

An AF fighter squadron receives last-second notification it is needed for a deployment to an austere location with a damaged runway. In order to operate quickly, the runway needs repaired first and shelters need to be constructed for aircraft protection. Fortunately, the USAF spent the last 20 years researching AM and possesses the most advanced concrete printer in the world. This system is mobile, it can drive itself up and down the runway, scanning for potholes, automatically printing a perfectly shaped reinforcement structure and concrete fill pattern specific to each pothole. Next, the machine makes its way over to the ramp, where it begins printing individual shelters for each aircraft. When complete, the machine spends the rest of its time printing perimeter blast walls, housing, and office space that both protect the base and add to productivity.

Once the runway is secure, the fighter squadron – complete with mostly 3D printed autonomous wingmen – arrive to the base. After each mission, the aircraft are scanned for battle damage, and when necessary, the AF's latest aircraft skin-repair technology is available. This system will make a perfect scan of the aircraft's damaged skin, automatically correlating the section with internal engineering specifications, and on the spot a perfect patch or entire panel is printed to repair the aircraft. Likewise, the internal structures of the aircraft were printed with embedded sensors, allowing maintenance to anticipate repairs to overstressed parts in advance.

Back in the operations building, intelligence Airmen are briefing today's mission, and they've conveniently printed an exact replica of the terrain and target area where the formation is scheduled to fly a low-level bomb run into hostile territory. The 3D model reveals all the pinch points in the route and target area, giving the aircrew full awareness of the area before they ever see it in person. Before walking out the door, the pilot dons a perfectly printed helmet and body armor, tailor-made for each individual. In fact, every Airman, Soldier, Sailor, and Marine is now much more mobile and comfortable, because they're outfitted in custom printed protective gear.

In this future scenario, the Air Base Wing Commander no longer requires complicated logistics trains and supply storage. Instead of deploying fifty people to manage thousands of critical parts and supplies, the Commander employs a handful of Airmen to monitor a dozen raw materials and several 3D printers. The simplicity and convenience of just-in-time manufacturing is at the commander's (and more importantly, the user's) fingertips. From aircraft repair to replacing human limbs in surgery, needs are met in a matter of minutes as opposed to hours or days. Flying parts in from across the globe is no longer necessary, and the service is leaner, safer, and better equipped to adapt to the battlespace.

SNAPSHOT: The Future of AM in the US Army

With the completion of repairs to the runway complete, the 82nd Airborne Division's 1st Brigade Combat Team (BCT) is ready in less than 24 hours to fly in to the joint operations area. Once on ground, 1st BCT's engineer battalion immediately gets to work by deploying their own organic 3D printers to build barriers, fortifications, living quarters, an expeditionary role II medical facility and an expeditionary supply-support activity (SSA). Upon completion of the SSA, the brigade support battalion (BSB) immediately moves in, deploys their own organic 3D printers and begins manufacturing high demand items identified prior to the deployment and not

immediately available from the authorized stockage list or bench stock. The BSB's C Co assumes the role II facility and begins coordinating basic medical aid. With the help of their own 3D printers, medical personnel manufacture lifesaving items and quickly return paratroopers to the fight. Follow on forces begin to arrive from the remaining BCTs of the 82nd. The Sustainment Brigade brings with it a vast array of AM devices that ramp up production for all classes of supply. The combat aviation brigade (CAB) hits ground and immediately provides close air support and with the aid of its own 3D printers, manufacturing on-demand parts to repair its aircraft in record time. The Division headquarters finally arrives to see its full complement of combat power and combat support established faster and better equipped than ever before. With the help of AM, the 82nd is ready to transition to the offensive and seize the initiative.

SNAPSHOT: The Future of AM in the US Navy

Meanwhile, a section of carrier-based F-35Cs patrols the skies on a close air support mission in support of friendly coalition forces. After completing the mission and refueling with a tanker, a message pops up on one of the pilot's displays indicating that a part on the aircraft has reached an operational limit and requires replacement. Even before the pilot can process the information, a secure message arrives onboard USS KENNEDY (CVN-79) where a maintainer checks to see if the specific part is available in the ship's supply inventory. Unfortunately, the part is showing a zero balance. The maintainer dutifully forwards a part order to a supervisor who approves the request to have the part produced by the additive manufacturing (AM) section of KENNEDY's Aircraft Intermediate Maintenance Department (AIMD). Upon receipt of the request, sailors in the AM section of AIMD simultaneously draw the requisite material, securely download the manufacturing specifications, and ready the 3D printer housed on its

gyroscopically stabilized platform. Hours later, the part is complete and a quality control (QC) specialist inspects the part for airworthiness. As the F-35C lands onboard KENNEDY, the part has passed QC and squadron maintainers greet the aircraft with part in hand, ready to return the aircraft to the fight.

WHAT NEEDS TO CHANGE FOR THE DOD

This scenario represents an ideal model for the Department of Defense (DoD) to implement in the future, but there are several changes that need to occur before AM can reach its full potential. The most notable areas of institutional change required for AM to reach its full potential are defense acquisition and unity of effort across the DoD, the joint logistics system, and intellectual property rights/contracting.

The three step Defense Acquisition Process

Defense acquisition contains three steps for the implementation of a new weapon or automated information system. Before a systems can become a concept, the Joint Chiefs of Staff (CJS) must identify a requirement for the joint force in a capabilities based approach called the Joint Capabilities Integration and Development System (JCIDS).⁶¹ From JCIDS, an initial capabilities document (ICD) identifies either a non-material (such as a change in strategy or tactics) or a material based solution. If a material based solution is the consensus then the capability goes into step 2 of the acquisition system which is budget execution. The budgeting process takes place in four steps: planning, programming, budgeting and execution (PPBE)⁶² – with a goal of providing DoD with the best equipment while maintaining fiscal constraints.⁶³

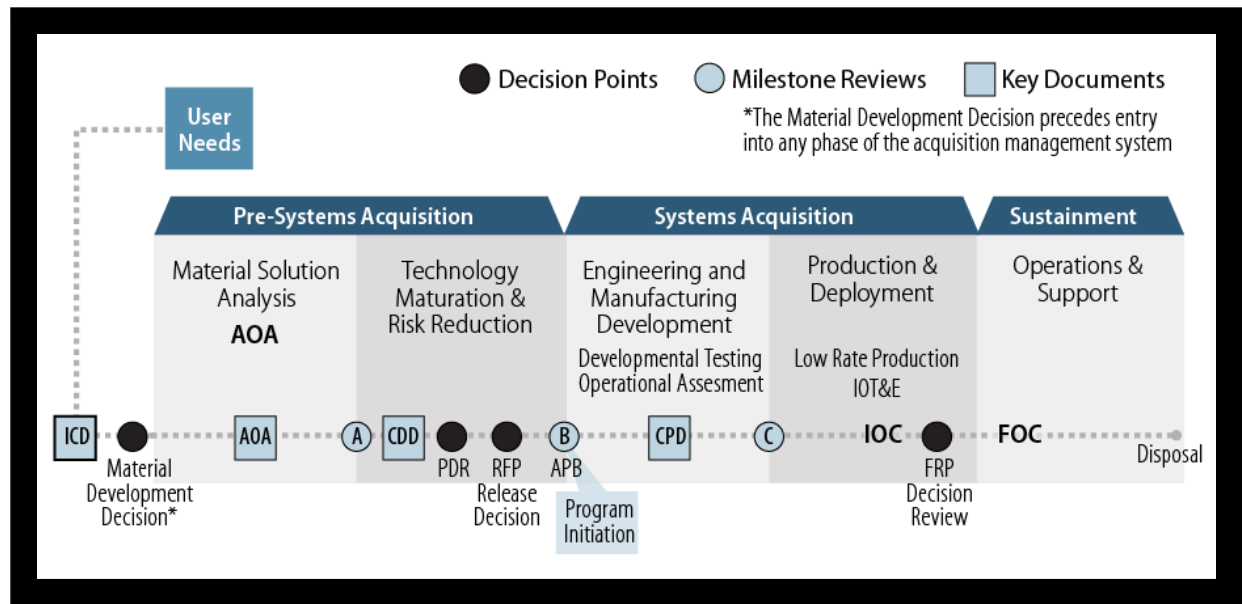


Figure 5: The Defense Acquisition System⁶⁴

In the last step, the defined material capability enters the defense acquisition system (DAS) which is governed by three milestones.⁶⁵ Prior to reaching milestone A, acquisition professionals assess the material solutions against alternatives and an overall strategy emerges to fully implement the capability throughout its lifecycle. A milestone decision authority (MDA) reviews the information and decides to progress past milestone A or terminate the program. During this phase a program manager (PM) and program executive office (PEO) emerge to provide oversight throughout the process. If moved past milestone A, existing technology is able to meet the desired capability and stay within budget. As milestone B draws near, engineers scrutinize the technology yet again with a preliminary design review (PDR). Prototypes follow the PDR and industry begins to bid for contracts. Again, the MDA assesses the program and determines if it will pass milestone B. Once past milestone B, the program officially becomes a program of record and designs are highly tested to ensure they meet the capabilities as defined by the guidance documents. When the design has proven itself to stand up to the rigorous testing

parameters, a capabilities production document (CPD) emerges and the MDA again reviews the information. The MDA makes the final decision to proceed past milestone C where the capability will enter initial low rate production, further testing and finally full rate production. The last and most costly portion of the DAS is the sustainment of the capability all the way through retirement.⁶⁶

Why the defense acquisition process doesn't work for AM

Current defense acquisition is overwhelmingly set up to acquire major weapons and automated information systems. While AM does not fall into either category, the potential capability it can provide to the warfighter deserves the exact same oversight that a major weapon or automated information system receives. Because AM is not a weapon or automated information system and doesn't fall into the Defense Acquisition System (DAS), there is also a lack of unity of effort across the DoD which results in uncoordinated efforts by the independent services that are not benefiting DoD as a whole.

The three step process for defense acquisition (JCIDS, PPBE and DAS) is not suitable for AM's incorporation throughout the DoD. Even though AM has been highlighted in high level strategic documents such as *Joint Concept for Logistics* as an important future capability – that “could have an important impact on mission success while potentially also providing a significant return on investment”⁶⁷ – the JCS has yet to identify it as such. Even if the JCS did identify AM as such a capability and draft an ICD and determine a material solution was necessary, AM would have a hard time fitting into the DAS which is setup to incorporate weapons and automated information systems throughout a lifecycle that can last significantly longer than the intended design life. As a result of the lack of AM's identification through JCIDS, the independent services have taken it upon themselves to develop AM to meet their

immediate and near future needs. The resulting disjointed efforts throughout the DoD has given rise to several separate AM centers who until very recently had not collaborated.⁶⁸ For example, the Army has embraced AM for the production of high demand fasteners that have stood up to the demanding environment in Afghanistan.⁶⁹ Meanwhile, the Navy has installed 3D printers on some select ships to produce on-demand items not available through shipboard inventory⁷⁰ and the Air Force has even began printing antennas and electric components.⁷¹ All of these efforts have benefitted the services in some regard, but the lack of synergy across the DoD is hindering AM from reaching its full potential.

How DoD can modify the defense acquisition process to incorporate AM

To correct these issues and to allow AM to reach its full potential, the JCS must identify AM as a critical capability. Without strong guidance from top echelon leadership, the services will continue to conduct disjointed efforts that may benefit themselves, but not DoD as a whole. Also, the DAS requires slight modification to accommodate AM. For continued oversight, a PM and PEO should be setup to provide the same oversight that major weapons and automated information systems receive. AM must be thought of as a major acquisition program, but the key difference is that it is not a weapons or automated information system that will have a 50 or 100 year service life. AM will continue to move so fast that milestone C will become irrelevant and any 3D printer acquired will never make it past low rate initial production before a better model with added capability is available. Also, DoD needs to designate a lead service, such as the Defense Logistics Agency (DLA) and mandate collaboration summits on a recurring basis. While JCIDS, PPBE and DAS might not provide the framework for the full incorporation of AM, parts and pieces of the process will serve AM well, most notably the identification of the

capability through JCIDS and the creation of a PM and PEO. When these changes eventually occur, another obstacle that AM will face will be the joint logistics system.

The joint logistics system and the Joint Logistics Enterprise (JLent)

The joint logistics systems is an interconnected web of agencies comprised of both government and private industrial resources. The combination of these resources results in the joint logistics enterprise (JLent) which meets the needs of the force by revolving around three imperatives: unity of effort, JLent visibility, and rapid and precise response; and seven logistical functions: deployment and distribution, supply, maintenance, logistic services, operational contract support (OCS), engineering, and health services (HS).⁷² To deliver a rapid and precise response to the warfighter's needs the JLent has instituted a two level maintenance system of field and depot. At the field level of maintenance, the primary goal is to return a piece of equipment back to operational status in the least amount of time. While at the depot level complete overhaul of assemblies and sub-assemblies occur which field maintenance is unable to perform.⁷³ Both levels require strict inventory management to ensure that the right part is in the right place at the right time.⁷⁴ To meet the inventory needs of the joint force, the JLent has setup vast amounts of storage and warehouses worldwide to keep a physical inventory stocked in accordance with the demands of the force.⁷⁵ As a result a heavy burden falls on US Transportation Command (USTRANSCOM), which is responsible for the delivery of inventory by land, air and sea, and DoD pays a heavy price tag to transport, store and maintain the requisite inventory.⁷⁶

How AM can change JLent for the better

AM has the potential to augment the JLent with increased efficiency and lower cost. While AM currently cannot completely replace the two level maintenance systems or the

physical inventory apparatus, the benefits of AM even on the smallest scale of implementation result in meeting the warfighter's needs faster than the current JLent.⁷⁷ DoD must integrate AM into the existing logistical system to ensure that the joint force maintains its advantage over adversaries.

There are several ways in which AM increases efficiency and reduces cost in existing supply chains. With several aging air and naval assets remaining in the US arsenal well past their service lives, parts to repair such assets have either dried up from the inventory or are no longer produce by original equipment manufacturers. By using 3D printing in combination with laser scanning technologies, reproduction of obsolete parts becomes relatively easy. Veteran aircraft and ships such as the B-52 and Ohio class nuclear submarine have embraced AM and extended their service in turn.⁷⁸ A transition from completely physical inventory to a mix of physical and digital inventory will also improve the current JLent. By reducing some of the need for large forward based stocks, AM once again provides cost saving by reducing non-demand supported inventory and transportation of finished products from manufacturer to warehouse.⁷⁹ Lastly and most importantly, AM offers the DoD the possibility of producing parts at or near the intended point of use. By placing 3D printers in the field with the warfighter, physical inventory and transportation costs can see significant reductions in overall budgets.⁸⁰

How the JLent needs to change for full incorporation of AM

Unlike most organizations, the DoD is unable to quickly embrace disruptive technologies like AM due to the nature of its mission and constant risk to human life. Even though the current JLent is rapid and responsive with current technology, AM offers significant savings when merged into existing processes. For AM to reach full incorporation, the JLent will need to fully embrace digital inventories over enormous physical stores by building secure data repositories

that are accessible to the most forward deployed warfighters. The transportation system that enables the JLent will also have to transition from being a parts supplier to being a material supplier. No longer will TRANSCOM have to move finished parts, but instead blocks of plastic, metal and ceramic will fill the cargo holds of airplanes, ships and trucks. To complete full incorporation, 3D printers must be in the possession of forward sustainment units and staffed by trained personnel who are able to process, build and certify AM parts. With these three steps complete, the JLent can change to incorporate AM, but one last issue emerges during the process and that is intellectual property rights/contracting.

Intellectual Property Rights

Creations of the mind such as inventions, art and literature all fall under intellectual property. From this broad category, intellectual property can then be broken down into two groups. First is industrial property which covers inventions, trademarks, designs and geographical indications. The second group concerns film, literature, art, architecture and recordings.⁸¹ Intellectual property allows creators to benefit from their work and protections have been setup to ensure re-creation does not occur without consent. Intellectual property rights have a long standing history dating back as far as 1883 at the Paris Convention for the Protection of Industrial Property.⁸² To ensure continuing adherence to intellectual property rights, the United Nations (UN) has chartered a specialized organization called the World Intellectual Property Organization (WIPO) to “ensure that the rights of creators and owners of intellectual property are protected worldwide, and that inventors and authors are therefore recognized and rewarded for their ingenuity.”⁸³

Contracting

Throughout the defense acquisition process, contracting officers are continually working with original equipment manufacturers (OEMs) to supply major systems with parts, tooling, etc. to ensure a system passes milestones and lasts throughout the intended lifecycle. Under current manufacturing techniques and analysis, engineers are able to determine a particular part's failure rate. Contracting officers analyze the failure rate and contract with the OEM to maintain a certain percentage of overage of a given part to ensure demand is met and a contingency reserve is available. It is common for contracting officers to go above the failure rate by at least 1% to account for such contingencies.⁸⁴

How intellectual property rights and contracting hinder AM implementation

Since the DoD relies on industry and private resources to bring their identified capabilities to reality, the end items that populate the US arsenal contain intellectual property that must be paid for. Unfortunately, the DoD has failed to secure licensing rights for major items for quite some time.⁸⁵ Manufacturers produce the quantity the DoD sets forth in its contracts, but if demand increases outside the parameters set forth in the original contract, the DoD has to pay a second time. These procedures do not work well for AM's incorporation. To transition to a digital inventory to enable AM, the DoD will have to purchase the rights for products up front at a potentially greater initial investment than previously thought of.⁸⁶ There will also be issues with the re-creation of obsolete parts such as in the case of the B-52 and Ohio class nuclear submarine mentioned above.⁸⁷ Contracts will need to change as well. No longer will a 1% buffer be a requirement for a contingency of overage of spare parts. AM's on-demand capability nullifies the need to maintain such large overages and saves money in the long run. By

paying up front for data rights and modifying contracting practices, the DoD can eliminate hindrances to AM's implementation and allow it to reach its full potential.

Changes Needed: Conclusion

AM offers the DoD the opportunity to meet the needs of the warfighter faster, more reliably and with greater precision. While industry continues to adopt AM at a steady pace, the DoD, due to its inherent risks, has not embraced AM with the same vigor. Until senior echelon leadership acknowledges AM capabilities as the transformative technology that it is proving to be through the JCIDS process the result will continue to be disjointed efforts by the independent services that are occurring today. As a transformative technology, AM must be regarded as a major acquisitions project and as such, a PM and PEO needs to be setup to provide the exact same oversight that a major weapons system receives. There also needs to be a lead agency, such as DLA, appointed to monitor and control DoD wide efforts. With minor changes to the three step defense acquisitions process (JCIDS, PPBE and DAS), AM can be on a road to full implementation DoD wide. The JLEnt also requires slight modifications for AM to achieve its full potential. By transitioning from a pure physical inventory to a mix of a digital/physical inventory, the JLEnt can increase efficiency and reduce costs. Transportation and warehousing requirements will change due to this transition as TRANSCOM moves from shipping finished products to shipping materials to forward stationed 3D printers. Lastly, before AM can reach its full potential, DoD will need rework its policies on intellectual property and contracts. With a digital inventory in place, DoD will have to pay upfront cost to acquire data rights that may come at a higher price tag than what is now acceptable. With the benefits of on-demand creation of parts, DoD will no longer need to write into contracts stipulations for overages in excess of predicted failure rates. For AM to reach its full potential in the DoD, these three obstacles must

be overcome. Disruptive technologies are always difficult to incorporate into a proven structure, but AM possesses the capability to increase the US advantage of its adversaries and is worth any aggravation that it may cause.

CONCLUSION

Throughout history transformative technologies have taken significant time to develop as universally acceptable methods. Manufacturing has seen a slow and steady transition from household hand made products, to specialized guilds and finally to machine based industries. During these transitions, man has slowly embraced devices designed to increase efficiency while lowering the need for highly skilled labor. As efficiency increased, so too did output and products were able to be made in mass quantities. With the advent of the computer and robotic technologies, manufacturing reached previously unimaginable levels of efficiency and began to rapidly replace man on the production floors of industry. This trend continues to this day as AM slowly makes its way into manufacturing and offers to increase efficiency and production once again.

AM has been around since the early 1980s. Originally embraced by manufacturing as a rapid prototyping tool capable of quickly bringing designs to physical form, AM has increasingly advanced to the point of producing complex physical parts with the same quality of traditional subtractive techniques. Originally setup to produce plastic and polymer parts, AM processes have grown to include metal and composites. Even the medical industry has begun to embrace AM with the ability to produce individually fitted prosthetics now available and printed organs a distant goal. AM is also enabling home users to skip the factory and print parts on-demand to meet specific requirements.

Presently, industry is slowly incorporating AM into existing organizational structures. High tech aerospace companies, such as ULA, have embraced AM for the creation of small in-house parts like brackets, panels and covers, but the demanding standards of space travel has hindered AM from reaching its full potential. With only one AM machine on the production floor at ULA in Decatur, AL, there is a lack of material capacity and many barriers preventing the engineering team from fully incorporating AM into their structure. ULA's incorporation of AM is very limited at this point, but serves as a useful model for DoD going forward. Space, like defense, has inherently extreme risks associated with it and embracing unproven technologies too quick can have disastrous effects. Even though industry and DoD has been slow to embrace AM, it is possible to see the impact it will play on the joint operational environment 30 years from now.

The contested norms and persistent disorder enveloping the nature of conflict in the Joint Operational Environment 2035 must be met with more agility from the military.⁸⁸ From damaged runways, ramps, and shelters, to aircraft repair, it's obvious where 3D printing can impact the future. Shortening the supply chain for the entire 82nd Airborne Division and affording them their own organic 3D printers to build fortifications, shelters, medical facilities and warehouses is no small task, but to the end-user it represents the ultimate in flexibility and supply chain management. And, if platforms like the USS KENNEDY (CVN-79) were able to extend their time underway without constant worry about which part is going to run out first, the impact to operations would be immense. These scenarios are ideal, but they aren't fantasy, and they directly meet the challenges outlined in JOE 2035.

Three changes that must occur for AM to reach its full potential are defense acquisition and unity of effort across the DoD, the joint logistics system, and intellectual

property/contracting. Defense acquisition is a complicated process that occurs in three steps: JCIDS, PPBE and DAS, and is not suited for the incorporation of a non-weapons system such as AM. JCIDS identifies capabilities that the joint force lacks and determines if a material solution is feasible or not. Currently, JCIDS has not identified AM as a critical capability which has led to the independent services incorporating AM on their own terms with little coordination amongst each other. No lead agency or DoD lead has been appointed to resource and coordinate AM DoD wide. When JCIDS identifies a material solution is needed, PPBE allocates money to a project and moves the project into the DAS. The DAS is setup to acquire major weapons and automated information systems that must last 50 years or more. DAS uses three milestones to progress a project that are practically irrelevant for the incorporation of AM. AM technology is moving too fast for the DAS and 3D printers cannot be thought of as a system which will last 50 years or more.

The joint logistics systems is a network of DoD and private industrial resources. The system is built upon forward based warehouses that stock vast amounts of material and parts. A heavy reliance is placed upon USTRANSCOM to ensure the delivery of finished parts continually meets the demand of the warfighter. To incorporate AM, the JLENT must transition from a physical inventory to a digital inventory. Instead of finished parts, warehouses will store large data repositories and unfinished materials that can be rapidly loaded into 3D printers to create on-demand parts.

The last change that needs to occur for implementation of AM is DoD policy on intellectual property rights and contracting procedures. Intellectual property is a creation of the mind that must afford the creator some benefit and several protections exist to ensure that happens. DoD has not licensed technical rights for end items for several years and for 3D

printers to produce a part, money will have to be paid to the creator at a higher upfront cost.

Contracting procedures currently apply and overage to a determined failure rate of a given part to ensure demand is always met with some wiggle room for contingencies. Since AM offers part creation to meet exact demand, contracts will no longer have to include a typical 1% buffer over the predicted failure rate. With these three changes, AM can be on a path to full incorporation throughout the DoD.

AM is perhaps one of the most profound technological advancements of the past 50 years. As such, AM's full potential excites as well as scares industry and the DoD. Just as the cotton gin and the assembly line shook up industries during their own time, AM is threatening to do the same to accepted manufacturing methods today. While AM is not fully ready to take over traditional methods just yet, implementation on a small scale now will pay dividends in the future. For the DoD to keep an advantage over its adversaries, it must remain on the cutting edge of manufacturing processes to ensure that the warfighter always has what he needs, when he needs it and where he needs it. AM offers the DoD the opportunity to accomplish its mission faster and with more precision. The joint operational environment in 2035 will undoubtedly be augmented with AM capabilities, and to ensure this is a reality, the DoD must continue to invest heavily in AM technology while substantially changing policy to accommodate this new reality.

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