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ABSTRACT: Advanced manufacturing, particularly additive manufacturing, will drive economic growth over the next several decades. Disruptive technologies in the manufacturing sector will upturn traditional business practices and impact national security issues from supply chain management and weapons design to nuclear technology proliferation. Nations willing to commit to innovation within this new industrial revolution will increase their economic standing and improve their military capability; both critical elements in achieving one's national security objectives. The key to America's advanced manufacturing dominance is the nurturing of innovation clusters, incentivized by government, which builds collaborative environments between academia and industry under the government's strategic vision for national prosperity. Additionally, precise government initiatives that foster innovation and encourage risk-taking in the additive manufacturing field, without stifling private sector initiative, are critical to assuring America's ability to globally lead.

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Industry Study Outreach and Field Studies

On Campus Presenters:

10 FEB 2017	MANTECH	Washington, DC
13 MAR 2017	Bureau of Labor Statistics	Washington, DC
28 MAR 2017	HP	Washington, DC

Field Studies – Domestic:

01 DEC 2016	White House Office of Science and Technology	Washington, DC
03 FEB 2017	Naval Research Lab	Washington, DC
17 FEB 2017	Boeing Advanced Manufacturing Center	St. Louis, MO
23 FEB 2017	Power America	Raleigh, NC
	Nonwovens Institute	
	Biomanufacturing Training and Education Center	
	FREEDM Center	
24 FEB 2017	CREE/ Wolfspeed	Durham, NC
	Windlift	Raleigh, NC
	Lord Corporation	Cary, NC
27 FEB 2017	Tech Shop DC	Arlington, VA
16 MAR 2017	Carbon Fiber Technology Facility	Oak Ridge, TN
	Local Motors Micro Factory	Knoxville, TN
	IACMI	
	University of Tennessee	
03 APR 2017	Lorain County Community College	Elyria, OH
	RP + M	Avon Lake, OH
	Humtown Products	Leetonia, OH
04 APR 2017	America Makes	Youngstown, OH
	Ansys	Cecil, PA
	Carnegie Mellon University	Pittsburgh, PA
05 APR 2017	Penn State University	University Park, PA
	Arconic	New Kensington, PA
06 APR 2017	Allegheny Technologies Incorporated (ATI)	
	-Brackenridge	Pittsburgh, PA
	GE	
	ATI- Oakdale	
07 APR 2017	ExOne	N. Huntingdon, PA

Field Studies – International:

24 APR 2017	Advanced Manufacturing Research Center	Sheffield, UK
25 APR 2017	University of Nottingham	Nottingham, UK
	Renishaw	Staffordshire, UK
26 APR 2017	Manufacturing Technology Centre	Coventry, UK
27 APR 2017	BAE	Blackburn, UK
28 APR 2017	Defense Science & Technology Labs	Porton Down, UK
	National Composites Center	Bristol, UK
02 MAY 2017	Fraunhofer	Dresden, Germany
	Concept Laser	Lichtenfels, Germany
03 MAY 2017	ExOne	Gersthofen, Germany
	EOS	Krailling, Germany

INTRODUCTION

Scope and Thesis

Advanced manufacturing (ADMAN) refers to new technologies and improved processes that result in more efficient manufacturing techniques or higher quality products. Within ADMAN, additive manufacturing (AM, also known as "3D printing") emerged as a disruptive technology with the potential to reshape industry as we enter a fourth industrial revolution (this is probably worthy of definition). 3D printing has numerous economic and national security implications that must be examined and considered when drafting future American strategies. AM represents opportunities for simultaneously promoting U.S. economic growth and national security by increasing the speed and flexibility of design and fabrication, reducing costs, restructuring supply chain management, reducing dependency on foreign suppliers, and improving the competitive advantage of U.S. industry. At the same time, these techniques carry risks of displacing existing domestic economic structures, enabling adversaries to manufacture threatening technologies, and exposing new attack vectors against the U.S. defense infrastructure. Although AM will grow as a result of natural market forces, targeted polices and limited investments will empower the U.S. government to leverage this process toward its own economic and national security interests as these technologies transition from research and development (R&D) to large-scale operations within the global economy.

Methodology

This study will provide an in-depth examination of 3D printing; taking a holistic look at the AM industry based on academic research, classroom instruction, engagements with experts, and site visits to numerous factories, research facilities, corporate offices, and institutes of higher learning. An industry definition of AM will be followed by an examination of its current state, including advantages when compared to traditional manufacturing methods as well as the challenges brought about by AM's injection into the world economy. The paper will then pool findings from research and discussions with AM industry leaders and government officials, both domestic and international, to forecast the trajectory of 3D printing and discuss the potential roles of government along that path. On this journey, the narrative will touch upon four critical areas that will shape the development and impact of AM over the next decade: the government-industry-academia nexus' (triple helix) ability to spur innovation and growth, changing needs in workforce education, threats to national security, and Department of Defense (DoD) applications. As these considerations intertwine, policy recommendations will be presented based on the evidence collected and analysis executed over a four-month long process of research, study, site visits, and engagement with industry and technology experts.

ADDITIVE MANUFACTURING DEFINED

AM encompasses an innovative and diverse group of industrial segments that have the potential to transform the conception, design, and production of goods in ways not seen since the Industrial Revolution. "3D printing is a form of additive manufacturing technology where a three-dimensional object is created by laying down successive layers of material. 3D printers offer product developers the ability to easily print parts and assemblies made of several materials with different mechanical and physical properties in a single build process."[1] The National Council for Advanced Manufacturing describes AM as the "extensive use of computer, high precision, and information technologies integrated with a high-performance workforce in a production system."[2] AM uses computer-aided design technology to allow "a product to be built up from nothing," unlike subtractive manufacturing that "cuts down from a larger object" or formative manufacturing that uses molds, casts, and dies "to form materials into a desired shape."[3] This industry provides a multitude of benefits through a variety of differentiated sectors and applications.

Sectors under the AM umbrella include AM systems, materials, supplies and services, all of which serve a diverse group of industry sectors. For standard manufacturing processes, traditional manufacturing remains the more viable option. However, AM provides an attractive alternative that enables customization, flexibility, functional optimization, and low volume production of complex parts in areas such as prototyping, modeling, product development, and innovation. Each manufacturing process has benefits and tradeoffs, therefore considering needs and priorities is essential when deciding between additive and traditional manufacturing. Critical to the success of these AM sectors is the availability of materials with the right physical and chemical properties that make it possible to use AM technology to produce desired goods. Common materials used in AM include plastics, polymers, metal powders, and composite materials such as glass, ceramics, and cermets (ceramic-metal hybrids). Growth in the AM industry has increased demand for material, thus attracting more material suppliers into the market.

AM makes many benefits possible across all sectors, including complex geometries, durability, strength, and weight reduction. For decades, traditional manufacturing involved inherent limitations, including complex geometries which cannot be produced through standardized methods. As a result, this led to the common practice of creating larger parts in subsections, then bolting or fusing them together to create the final assembly. Innovation and technology advancements through 3D printing have created a new paradigm where previously unattainable assemblies can be printed as one integral part. This improved part durability and strength, while also eliminating the need for expensive, heavy adjoining hardware. Airbus' implementation of AM technology provides a premier example of its potential for printing airframe parts. By using AM, Airbus' new production processes will create "parts up to 55% lighter than traditional parts, and they will be stronger. They will also be created with a new manufacturing process that consumes 90% less energy, uses 95% less raw material, and allows Airbus to consolidate components as well as avoid tooling, cutting the number of production steps in half."[4]

Another major advantage of 3D printing is the ability to rapidly create prototypes. Prototyping allows companies to develop visual models, while gauging proper fit and sizing of items to facilitate further design, development, and production efforts. Reducing time and costs associated with producing prototypes provides firms with increased agility to respond to changing customer demand. One of the greatest advantages of prototyping is bypassing the need to meet the same functional specifications or certifications as final products. This enables parts to be 3D printed to the required form and fit at a fractional cost. An example of this application comes from Boeing's F-18 production line in St. Louis, Missouri. During the design of a new external conformal fuel tank, aircrews expressed concern about the impedance on aircrew ingress/egress. Since this limitation was identified during the design phase, Boeing 3D printed an actual conformal fuel tank prototype to conduct testing. The prototype tank did not require the same fuel tank plumbing or metal specifications, thus meeting design testing with relative ease. According to a Boeing official, "At 26 feet long, the tank was printed in under a week and served its purpose at a fraction of the cost."[5]

An additional AM benefit is the capability to rapidly create tooling on-demand, or eliminate the tooling requirement entirely, introducing an unprecedented level of flexibility. AM delivers the capability to print parts from drawings, or reverse engineer parts, without costly investments in specialized tooling.[6] Printing traditionally manufactured parts, when cost effective, may eliminate the need for molds or casts. Additionally, manufacturers may achieve dramatic cost and time savings by 3D printing the mold or cast itself, particularly for low-use and unique items. Boeing's St. Louis manufacturing facility profoundly improved production processes by printing tooling components in merely days, or even hours, rather than relying on the normal year-long acquisition timeline.[7]

The 3D printing-based industry shows tremendous promise. As of 2015 there were 151 companies in the 3D printing and prototyping services industry, with 12.8% annual growth projected through 2020.[8] As material and equipment costs continue declining in a maturing industry, experts expect competition to rise and the application of 3D technologies to continue proliferating. A healthy competitive model and remarkable growth rate indicate an industry that will expand over time. This mutually beneficial relationship between producers and consumers also creates tremendous and sustainable end user impacts. The very nature of AM enables innovative strides toward the production of cheaper, lighter, and stronger parts. Incorporating new materials such as carbon fiber or super alloys, while reducing multiple components to one complex printed part, will continue achieving production and performance efficiencies that reduce costs and further solidify AM as a key element of the production value chain. The DoD's operational energy costs consumed nearly $14 billion (B) in 2014,[9] (there are also significant energy savings for the DIB in manufacturing, and for DOD in limited manufacturing and depot MX) and the implementation of lighter components on DoD weapon systems will equate to direct and immediate cost savings. With abundant benefits for consumers of 3D printed end items and a rapidly increasing production base to provide them, the 3D printing industry appears postured for continued long-term success.

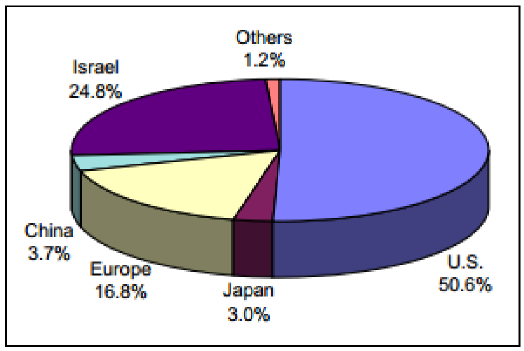
CURRENT CONDITION

The compound annual growth rate of the AM industry over the past 27 years is a robust 26%,[10] and is projected to continue growing. According to Wohlers Report 2016, the AM industry grew to $5.1B in annual revenue in 2015 with annual growth rates of 33.8% the previous three years.[11] 2016 estimates project the industry will grow to over $15B in 2019 and over $26B in 2021.[12] As research and development advance AM technologies, prices continue to drop, and innovation increases application across diverse industry sectors such as aerospace, automotive, medical/dental, manufacturing, defense, architecture, education, and energy, demand will increase and continue to drive industry growth at unprecedented rates.

The two primary segments of the industry are *products* and *services*, with industry revenues closely balanced between them. The *products* segment includes primarily the sale of AM systems (machines) and materials. The *services* segment includes primarily the sale of final products produced with AM systems. It also includes secondary market products such as tooling, molded parts, and castings, which make up about half of the services segment. Research shows that professional printers, ranging in price from $5K to more than $1M each, accounted for 78% of global revenues, even though sales declined -12%.[13] In comparison, the desktop/personal printer segment, carrying an average sales price of $1K, saw 27% growth.[14] Research and developers within industry and academia indicate that then enhanced capabilities and lower prices drove demand for desktop/personal printers, particularly in the educational sector. Industry leaders in manufacturing AM systems indicate that the demand for metal print capabilities will increase growth in the metal sector. The industrial AM systems market is moderately competitive and still early in the overall industry lifecycle, with innovation high and firms posturing for future growth by investing heavily in startups, acquisitions, and R&D.

AM material sales ($768M) kept pace with product sales by growing 20% in 2015. Photopolymers remain the largest segment (45%), with thermoplastics close behind (40%). However, the trend is moving towards metals (11%), with 49% growth in 2014 and 81% in 2015.

The U.S. dominates a globally competitive AM industry overall. Using the sales of industrial AM systems by region from 1988 through 2014 as a proxy, the U.S. is responsible for 51% of sales, Israel 25%, Europe 17%, China 4%, and Japan 3%.[15] However, the same metric in 2015 shows Israel leading with 41% of sales, largely due to a merger and subsequent registration of former U.S. industry giant Stratasys as an Israeli company.[16] Europe followed with 32% of 2015 sales, U.S. 17%, and Asia 10%.[17]



Source: Wohlers Associates, Inc.

Figure 2. Industrial AM systems sold by region

IBISWorld reports consistent projections of industry and market growth potential.[18] Continued AM process and material capability advancements are predicted to expand the manufacturing customer base, as capabilities remain strongest in the complex design, rapid prototyping, and tooling capabilities;[19] Currently, AM will continue to grow in its capacity to augment long-run production capabilities, rather than replace traditional manufacturing. However, the demand for long-run AM production will drive the competition and technological innovation needed to develop the more reliable, capable, and faster machines needed to enable mass production in the future.

The 2016-17 Eisenhower School ADMAN Industry Study visited several manufacturing innovation institutes, both domestic and international, receiving briefings from industry executives and experts at leading government and academic R&D facilities. This exposure challenged popular convention that AM will never scale up to the traditional manufacturing level and will remain relegated to rapid prototyping and tooling. “Hewlett-Packard (HP) released the HP Fusion Jet printer, which it said will be up to 10 times faster than existing machines and can cut the cost of manufacturing parts in half,” [20] while continuing R&D efforts to further enhance production speed capabilities.

A visit to General Electric’s Center for Additive Technology Advancement revealed that GE recently acquired international AM systems manufacturers Arcam AB (Sweden), Concept Laser (Germany), and SLM Solutions (Germany). Further research validates GE’s intent and new capability to supply additive machines, materials, and software for several industry segments, including aerospace, power generation, automotive, medical, and electronics.[21] Additionally, GE “has invested approximately $1.5 billion in manufacturing and additive technologies at GE's Global Research Center (GRC; Niskayuna, NY), in addition to building a global additive network of centers focused on advancing the science.[22]

Both HP and GE executives believe AM will economically scale up to traditional manufacturing competitiveness. Mr. Weber indicated that HP is posturing to become a market leader in absorbing a significant portion of the estimated $1.5T piece of the $13T global manufacturing industry that AM will displace.[23] The Chief Executive Officer (CEO) of GE, Mr. Jeff Immelt, stated that AM will save $3 to $5B in GE manufacturing facilities over the next few years alone.[24] This is significant because, as previously stated, the entire 2015 AM global industry revenue was $7B.

We should not easily dismiss these assessments as overly optimistic. Both companies successfully compete as multi-billion dollar, international corporate giants in their segments. As decade proven market leaders, they historically make shrewd investments. Stakeholder and stockholder oversight prevents unfounded enthusiasm from interfering with attaining return-on-investment targets. Stated otherwise, GE and HP stand confident in their current analysis and assessment of AM's potential to displace a significant portion of traditional manufacturing.

Analysis indicates that major firms are biding time while assessing technology direction, challenges, opportunities, and consumer reactions, while possibly observing patent timelines that protect intellectual property. Regardless of motive, the entry of Fortune 100 companies into the industry will undoubtedly improve the forecast of even the most pessimistic analysts. The AM industry enjoyed impressive growth rates for many years, and may now stand on the cusp of a transformative "tipping point" where the "Holy Grail" of long-run production becomes attainable. However, the industry must still overcome many challenges before achieving this goal.

CHALLENGES

Economic Challenges

The AM market faces microeconomic challenges that include new competition, service consumers, price stability, and industry standards. When considering new competition, decreasing material prices and potential government subsidies (in the form of government Innovation Institutes that partially offset some industry costs) contribute to an attractive AM *services* segment with declining barriers to entry and moderately strong new entry threats. The AM *products* segment faces slightly higher barriers to entry, creating average forces from new entry threats. High technology and patent protections form entry barriers that protect incumbents, although many patents are expiring. Some system manufacturers are hedging against future product segment commoditization by vertically integrating and diversifying into the services segment.

AM service consumers possess moderate purchasing power and negotiating leverage. In general, consumers operate within established business cases for traditional manufacturing methods and processes. Therefore, AM services must provide unique product designs or improved business cases to attract customers.

Price stability for extremely high cost systems inhibits rapid adoption by the traditional manufacturing industry. Short- to mid-term patents protect system suppliers resulting in artificially high system prices. This trend will continue until patents expire, technology diffuses, and more competition reduces pricing power. Even as prices fall, high transition costs may dissuade potential buyers from moving toward AM processes.

The lack of industry governing standards continues to constrain market potential. “Standards provide the customer confidence that measurement practices, processes, and terminology are consistently applied.”[25] The aerospace, automotive, and medical industries commonly employ standards in their production processes, as well as in final products. Defining accepted AM standards (e.g., powder manufacture, component design, processing, inspection methodology, etc.) across these industries through efficient credentialing bodies will ensure AM’s credibility as a mature production solution and more quickly expand business opportunities.

Workforce/Education Challenges

With AM growth outpacing its workforce, the sector struggles to meet rising demand for educated and skilled workers in the design, development, and production processes.[26] The AM industry must develop a capable, adaptable, and agile workforce, in response to the demand for equipment and machinery operators, engineers, researchers to advance the industry, and managers who can integrate the technology into manufacturing processes. Factors causing these skills gaps and workforce shortages include: rapid technological advances, off-shoring, trade imports from China and South Korea, less than optimal workforce training, insufficient recruitment and education programs, and contract manufacturing. In assessing government efforts to address these concerns, it is clear that while innovation and technology continues to improve efficiency within and competition among industries, innovation out-paces workforce training and development, creating a gap.

In addition to a workforce shortage, inconsistent approaches among various workforce development models have created an equality issue. One community college (CC) model utilizes government funds to implement a College Credit Plus program with K-12 schools. This program’s shortfalls include poor student acceptance metrics and the challenges with ensuring optimal teacher qualifications. Not only are college level instructors absent from this program (unless high school students take the courses on the CC campus), the CC is not a part of the high school faculty evaluation process. Another model, run by a land grant university, has K-12 schools located on campus and provides students with more resources and courses taught by university faculty. While both models involve partnerships and collaboration between industry and K-12 schools, they may differ in overall effectiveness. The latter model exposes students to advanced machinery which produces graduates who are more likely to be sought by companies such as Cisco, IBM, Netapp, and Boeing.

American’s prefer that their children attend a 4-year university following high school, rather than work in what they perceive as dirty, dangerous, less lucrative, and dull manufacturing jobs. Without a cultural change to begin thinking differently about the role of advanced technology in manufacturing today, the U.S. will be left behind as a global leader in technological innovation. Consequently, the U.S. economy will lose out on the industry’s potential employment, production, and trade benefits. Providing the manufacturing industry with a well-prepared workforce is ultimately a national security matter, as it is that competitiveness and economic strength which ensures our ability to remain the world's leading power.

Technology Challenges

Achieving product consistency, quality, and integrity is a challenge for the industry. A recent survey indicates that over 75% of industry experts believe a lack of finished product certification significantly hinders additive manufacturing.[27] Aerospace parts, particularly flight critical components, require Federal Aviation Administration (FAA) or DoD airworthiness certification. Automotive and medical component parts also require Original Equipment

Manufacturer or Food and Drug Administration (FDA) qualification or certification. Inadequately understood material distortion and shrinkage properties as well as deficient metal AM processes result in thermal stress and internal density parameters, which fail to meet required specifications. Post processing and inspection activities vary across manufacturers. Until these issues are remedied, the aforementioned industries will fail to realize the full potential of AM.

The material science of metals presents challenges to the qualification process of metal AM produced parts. Material science drives the variability of output between like machines. AM machines also use metal fusion to produce parts. Failure to understand both the material science and fusion process increases machine variation and reduces predictability. Researchers from the National Institute of Science and Technology (NIST) cite more than 50 factors that influence this fusion process.[28] Unfortunately, unsophisticated process control measures using simple trial-and-error methods contribute to inconsistencies.[29]

The AM industry lacks consistent in-process controlling mechanisms. An in-process control system provides machine performance feedback to the operator. Closed-loop feedback systems could inspect each layer of the build as it occurs. Ideally, real time adjustments could be made to enhance quality control by detecting and correcting defective conditions rather than completing defective parts.[30] In-process control benefits include a reduction in machine-to-machine variability, as well as reduced inspection time, overall processing time, and waste.

Security Challenges

AM, while presenting wonderful opportunity, also presents some security threats (discussed in greater detail in the forthcoming essay section) from offering adversaries additional capabilities, to presenting more opportunities to adversarial cyber attack or espionage. That said, AM offers the potential to reduce some security challenges by increasing, or at least maintaining Defense Industrial Base (DIB) autarky: relying on domestic suppliers to produce and sustain material for its military forces. Autarky helps provide security autonomy by ensuring international suppliers, and their parent states, lack the ability to restrict access to the instruments of military power.[31] As AM progresses from the research world into broad commercial use, a critical consideration is how this trend impacts the ability of the U.S. to maintain autarkic defense production.

Globalization presents a prominent challenge in securing autarkic AM capabilities. As multinational corporations (MNCs) increasingly dominate the international economy, the idea of state-based production begins to lose meaning. But perhaps more important than the rise of MNCs, is the wide diffusion of the foundational technologies needed to commercialize AM. Although many people typically link globalization to offshoring traditional manufacturing companies to low-wage countries, globalization also ensures a country's access to current technology.[32] This need for international expertise to maximize performance is particularly relevant for AM. Even though many foundational concepts emerged from U.S. academic institutions, leading contemporary AM companies often reside overseas, limiting the ability of the U.S., or any state, to maintain pure AM autarky.[33]

A related, but independent concern is whether it's possible to keep AM technology out of the hands of potential adversaries via export control. This threat includes both industrialized state, and perhaps more critically, non-state actors. Armed with AM tools and techniques, these actors could produce dangerous weapons beyond their previous capabilities that are also undetectable by current U.S. intelligence community practices.[34] As with autarky, globalization and its natural technology diffusion presents the biggest challenge to implementing an effective export control regime. AM technologies are practically dual-use by definition, capable of instantaneously switching from commercial to defense production, while complicating any attempt to design or enforce effective export controls and monitoring standards.

AM’s cyber dependency yields manufacturing speed, flexibility, and efficiency benefits inherently accompanied by cyber risks, threats, and vulnerabilities. The fundamental concept of Confidentiality, Integrity, and Availability (CIA) reveals daunting cybersecurity vulnerabilities when applied to the AM industry. Confidentiality protects proprietary (trademarked, copyrighted, patented) information, intellectual property (IP), 3D designs, and personnel and privileged data from unauthorized access. Integrity guards information against improper modification and includes non-repudiation, which ensures neither sender nor receiver can deny having processed the information.[35] Availability delimits what digital model data remains readily available and defines the response timeline needed. The section 7 threats and security essay provides more in depth analysis.

DoD Supply Chain Management Challenges

From a supply chain perspective, achieving standardized production includes several focus areas: IP protection, certifications, digital library security, raw material access, and gaining legal authorities to produce parts. Printers must meet specific certification criteria before successfully employing them to print certifiable parts. Attaining certification means every 3D printed part is the exact same as those that came before it. Designer certification will ensure all parts are built in the same manner regardless of machine or supplier. These processes must include standardized material specifications and machine settings to guarantee uniform properties of final components. A secure central digital parts library is a critical node for guaranteeing product consistency and comprises the final element of the production chain.

OUTLOOK

AM technology advances continue to reduce costs, increase printing speed, and enable printing in diverse materials, thus driving a slow but steady increase in market place acceptance and demand. This trend will continue to drive further improvements in AM speeds, materials, and object size to more quickly meet ever-increasing demand. Similar to Moore’s law with computing power, the AM industry will revolutionize manufacturing the same way the internet revolutionized information. However, just as the internet became used for destructive and disruptive purposes, so too can 3D printing, particularly with regards to Weapons of Mass Destruction (WMD).[36]

Short Term (1-5 Years)

AM adoption within the supply chain arena will continue growing to meet demands for low volume spare parts, rapid prototyping, and complex metal printing. As AM becomes more cost effective, it will dramatically reduce expenses for warehouse storage and delivery of spare parts to the point of demand. For example, the U.S. Navy is beginning the process of injecting 3D printing in to their supply system. "Additive manufacturing could bring about revolutionary changes to the Navy Supply System, with an associated paradigm shift from the current order and stocking system to implementation of just-in-time inventory," said Captain Kurdian after an event, hosted by Naval Surface Warfare Center Dahlgren Division. He went on to say "It has the potential to move the point of manufacture for hundreds of components and parts closer to the point of demand."[37]

Another trend will be increased AM usage by DoD and the DIB for rapid prototyping. Currently, traditional manufacturing's most expensive per unit cost comes from the prototyping phase. Developers optimize manufacturing lines for mass production of stable designs, vice one or two unique prototype items that continue design evolution. Hence, prototyping and production of low volume complex parts provide the greatest opportunity for AM to reduce costs.

Metal printing will grow rapidly as quality and capability continue improving. For example, "a V-22 Osprey completed its first test flight with a titanium 3D printed flight critical part…" announced Vice Adm. Paul A. Grosklags, NAVAIR commander. He went on to describe the future, "Although the flight today is a great step forward, we are not trying to 'lead' industry in our AM efforts, but it is absolutely critical that we understand what it takes to successfully manufacture and qualify AM parts for flight in naval aircraft, which we expect will largely be manufactured by our industry partners."[38]

Long Term (2020-2035)

AM market growth will accelerate as technology advances improve AM capabilities, particularly in molecular sciences, lasers, and computing power. To benefit from revolutionary innovation, DoD must grow a strong AM foundation to build upon. AM is much more complex than simply sending a Computer Aided Design (CAD) file to a 3D printer and hitting print. AM requires a certain amount of "art" coupled with an in-depth scientific understanding to effectively leverage a 3D system (powder, CAD, and printer). As Dr. Hans Langer, CEO of the private German company EOS, paraphrased it, "additive manufacturing requires a completely different way of thinking than traditional manufacturing that best comes from hands on use." He continued "once one's thinking has shifted you begin to see the revolutionary possibilities of additive manufacturing".[39]

U.S. private and public science and technology investments, combined with U.S. ingenuity, possess the potential to leverage AM to successfully achieve DoD's "third offset strategy," which refers to advancing the competitive advantage of America and its military allies by "by leveraging commercial sector innovation to develop the technological means to offset advantages or advances in anti-access area denial weapons and other advanced technologies that we see proliferating around the world."[40]. This strategy includes harvesting high potential technologies, such as HUNDA (Hypersonic, Unmanned vehicles, Nanotechnology, Directed energy, Artificial intelligence/Automation) in order to ensure continued U.S. national security capability dominance. For example, one potential AM application could involve R&D of a future hypersonic unmanned aerial vehicle (UAV). GE already uses AM in the GE9X, the world's largest jet engine, to achieve efficiencies not possible with traditional manufacturing. "Each engine contains 16 carbon fiber fan blades and 19 3D-printed fuel nozzles. The nozzles, which spray fuel inside the combustion chamber, replaced conventional nozzles comprised of more than a dozen welded parts. This helped reduce weight by 25%, increase fuel efficiency, and make it the company's quietest engine to date."[41] In a similar way that GE applied AM to break technical barriers in the commercial jet engine market, DoD can leverage AM capabilities to develop a hypersonic UAV.

By definition, the third offset strategy gives us a competitive advantage over our adversaries through innovative capabilities in HUNDA. However, the U.S. must protect innovation and technology from our adversaries for it to work. U.S. manufacturing success depends on continuous innovation, both in product differentiation and in manufacturing efficiency, which is increasingly reliant on automation, big data analytics, and the internet of things (IoT) to maintain a competitive advantage. Creating and operating this "digital thread," from design, through production, to field-product Wi-Fi monitoring, increases the risk of losing a competitive advantage to IP theft or sabotage, creating the digital thread paradox. The actual designs will be the competitive and comparative advantage for U.S. manufacturing and DoD's third offset capabilities. Protecting digital threads requires advances in combating cyber-crime, cyber-espionage, and cyber-warfare, with failure yielding critical economic and national security implications. While driving some level of protection, market forces will not solve the problem of increasingly capable state and non-state actors in the cyber domain.

Perhaps AM poses an alarming future threat in WMD. Dr. Grant Christopher's research identified some nuclear weapon risks. Per his abstract, "This paper examines the possibility of manufacturing critical nuclear-fuel cycle technology using 3D printers to circumvent export controls. It examines the near-term possibility of 3D-printing maraging steel for use in a centrifuge to enrich uranium. The paper finds that while significant technological challenges remain, an expert with access to an off-the-shelf 3D printer, advanced quality control technology, and knowledge of centrifuges should be able to achieve this."[42] Although an alarming threat when considering Iran and North Korea, it is exponentially more alarming when thinking in the context of non-state actors like the Islamic State of Iraq and Syria (ISIS) and Al-Qaida (AQ). While no open literature exists on 3D printing other WMD components, such as in chemical and biological weapon production, the capability to leverage 3D printing in "regenerative" medicine could theoretically be applied to creating chemical and biological "degenerative" asymmetric weapons. In fact, Bill Gates recently warned about bioterrorism stating, "advances in biology have made it far easier for a terrorist to recreate smallpox, a highly fatal pathogen, where there is essentially no immunity remaining."[43] In a similar warning, "the Nuffield Council of Bioethics warned that 'garage scientists' could unleash dangerous genetically modified organisms into the environment using unregulated technology already available online."[44]

The positive advantages of this next incredible revolution are pursuit worthy. While significant challenges and risks will permeate during the disruption, the AM Genie is out of the bottle. Those slow or refusing to change will be left behind

THE ROLE OF GOVERNMENT

The U.S. Government has multiple enduring interests, which include providing both security and prosperity for the U.S. population.[45] A chief factor in supporting these interests is a strong national economy. The link between a vibrant economy and national prosperity is obvious, but economic strength is also critical to having a strong national defense. Not only does the economy provide the tax revenue that funds our military and other security-related expenditures, it also provides the U.S. leverage over other actors on the world stage.

Is a strong national economy inherited or created? As Michael Porter has argued, while countries like the U.S. have been blessed with a wealth of natural resources, success in the global economy is increasingly defined by a nation's ability to create and absorb knowledge.[46] Thus a nation's competitive advantage is changeable and perishable. If the U.S. desires to maintain its position as the pre-eminent world power, it must take proactive steps to maintain its relative lead over competitors. While the U.S. political culture and our capitalist economy binds the role of government, the contemporary mandate for a proactive approach increases the need to clarify the government's efforts to establish and maintain the necessary conditions for promoting long-term economic success.

A key framework for understanding the role of government in maintaining a knowledge-based, innovation-driven economy is the concept of the triple helix. Emerging from academia in the 1990s, the idea of the triple helix is that "the potential for innovation and economic development … lies in … the hybridization of elements from the university, industry, and government to generate new institutional and social formats for the production, transfer, and application of knowledge."[47] In essence, fusing the relative strengths of academia, industry, and government make driving improved innovation in a knowledge-based economy possible, promoting aggregate economic growth and supporting our national interests.

The rise of AM provides a valuable case study for examining the broader concern of how the U.S. can seek to maintain its economic and political primacy. In recent years, globalization drove traditional manufacturing away from high-wage nations, but AM techniques along with a broader collection of ADMAN technologies hold the promise of disrupting traditional methods and promoting the "reshoring" of manufacturing to high wage countries.[48] This change would take place not because of protectionist trade barriers or other nationalistic policies, but from a changing economic calculus that could create natural incentives for industry to retain or grow their footprint in advanced economies. Such incentives include access to better regulatory environments, better trained workers, and large consumer markets. The result would allow industry to exploit synergies that evolve from producing products in places where they are designed and used.

The U.S. approach to leveraging the triple helix in motivating the commercialization of AM and ADMAN can be described as laissez-faire.[49] Traditionally, the U.S. invests heavily in early R&D programs through both academic institutions and government programs like national laboratories (e.g. Oak Ridge) and federally funded research and development corporations (FFRDCs). As argued by Linda Weiss, these investments, particularly in the security sector, served as a catalyst for growth in the broader U.S. economy.[50] Unfortunately, early R&D investments often fail to transition to commercial use. This so-called "valley of death" occurs because research institutions lose interest once basic scientific principles have been demonstrated, but industry is unwilling or unable to invest the funding required to bridge the gap to full-scale commercialization. To help address this problem, the Obama administration launched Manufacturing USA, establishing a series of consortia designed to facilitate connections between key triple helix actors in emerging ADMAN technologies. Each institute received $50M over five years under the premise that they would be self-sustaining by the end of that period.[51] Unfortunately, when compared to other countries' efforts, the U.S. program is underfunded and has an uncertain future. Some institutes (through a combination of limited funding and vision), act largely as a convening authority for industry, attempting to facilitate collaboration among natural competitors on a narrow set of issues. While this could help address joint challenges like developing technical standards, it also tends to keep companies from sharing their most valued IP. Some big U.S. firms are participating, but they often appear to be more interested in simply "keeping tabs" on their competitors rather than using the institutes to accelerate their own programs.

Germany has approached AM, ADMAN, and the triple helix from a different perspective. Employing a "balanced" configuration, they have long invested vast sums of government funds to operate the Fraunhofer institute.[52] Consisting of 69 distinct entities with 24,500 staff and an annual research volume of €2.3B, what began as a government-funded effort to facilitate the growth of German industry has morphed into a virtual corporation in its own right, one that is essentially a R&D entity for hire.[53] Fraunhofer continues to receive roughly 25% of its funding from the German government, but if individual institutes cannot attract sufficient industry investment they are subject to closure. This approach ensures relevance to industry and helps prevent unchecked bureaucratic growth. Although the Fraunhofer model may help extract commercial value from emerging technologies, it could very well stifle innovation by encouraging industry over reliance on external sources for product and process ideas. Finally, despite continuing to receive funding from the German government, Fraunhofer appears as concerned with growing Fraunhofer as it is with growing German industry as a whole. Its swelling investment of organizational resources abroad could conflict with German national interests.

The United Kingdom (U.K.) is employing a more refined take on the "balanced" approach to the triple helix. Like the U.S., the U.K. launched a series of innovation "catapults" designed to create regional innovation clusters in emerging technology areas related to manufacturing. Unlike the U.S., however, U.K. efforts are well resourced and unapologetically focused on growing U.K. industry writ large. The scale of U.K. investment resulted in facilities that are not only convening forums, but host large collections of state-of-the art machinery, technologies, and researchers designed to both attract industry investment and fund development of a new generation of researchers through sponsorship of graduate research at U.K. universities. Furthermore, while U.S. institutes seek to promote collaboration between industry competitors, U.K. efforts often segregate industry projects, allowing leading industry members to protect catapult-generated IP, and thus encouraging them to bring their toughest challenges to the institutes.[54]

Based on observations from the three models discussed above, the U.K.'s catapult approach appears to strike the best balance between accelerating commercialization of emerging technology, while still maintaining a strategic focus on developing a nation's industry. The rapid growth of industry involvement in the catapults provides convincing evidence that businesses find value in the interactions. But it is not clear that the U.K.'s model can or should be directly applied to the U.S. On one hand, U.S. investments in manufacturing technologies appear out of balance. We spend billions of dollars annually on basic science, with only a tiny fraction of federal funds dedicated to commercializing manufacturing technologies that could accelerate re-shoring. This shortfall should be addressed in numerous ways: re-allocating funds from basic R&D to AM/ADMAN efforts, providing more stability and longer time horizons for AM/ADMAN efforts, and allowing industry to access world-class government-funded research organizations like FFRDCs for company specific research efforts.

Simply setting the level or type of funding is not enough. Where these investments are made is also critical. To reap the full benefits of government investment, AM/ADMAN programs should be located based on the potential for synergies in the local environment, not simply targeting areas that need assistance because they've fallen on hard times. By planting such "innovation clusters" in the most fruitful soil, we raise the odds of success both for the local and national economy, while also encouraging regions to compete with each other to create the most favorable innovation conditions.[55] If areas exist where the local economy is faltering and local leaders cannot find a way to attract industry, the Federal government should consider funding programs to improve regional competitiveness (e.g. infrastructure or education investment) but it must resist the urge to place major AM/ADMAN efforts in places where they might not thrive. Although this approach could accelerate regional disparities, using a "best athlete" philosophy to direct AM/ADMAN investment would help provide the best overall economic growth by helping facilitate a recovery of U.S.-based manufacturing, improving our tax base, and thus increasing the federal resources that could be re-directed to improve conditions in less competitive areas.

Finally, the federal government must recognize that its approaches to taxation and trade are out of step with many global competitors. While domestic political realities complicate policy changes in these areas, failure to align our approaches with those of our economic rivals could put U.S. industry, and the broader U.S. economy, at a disadvantage in the global markets. The U.S. has unique advantages that should allow it to regain and retain leadership of global manufacturing. With limited, focused investment and coherent policies that leverage unique capabilities of each triple helix element, we can encourage innovation and empower our own industries to out-compete the rest of the world.

ESSAYS ON MAJOR ISSUES

1. AM Technologies and Trends

Traditional manufacturing consists of casting, forging, and injection molding, which require subtractive post processing, i.e., milling and drilling. Geometrical constraints limit traditional manufacturing capabilities. For example, if using traditional castings, parts require minimal cavities and specific shaping for easy removal from molds. Injection molding produces only solid parts. In contrast, additive manufacturing removes many traditional manufacturing constraints, essentially redefining possibilities. By building one layer at a time, AM produces complex parts with shapes and cavities never before possible. Additionally, AM enables the combining of multiple parts into one, with enhanced structural and functional efficiencies. AM also enables part production from several materials with different mechanical and physical properties in a single build process. AM incorporates weight reduction benefits by replacing traditional solid designs with organically designed shapes, maintaining structural performance with less material. Tooling and rapid prototyping exemplify key AM applications that increase production speed and save costs. Consequently, larger companies such as Ford Motor Company and General Electric employ desktop printers to accomplish rapid prototyping.[56] AM represents a game-changing technology for manufacturing industry producers and consumers.

Materials and Processes

Materials used in traditional AM processes include various polymers, composites, metals, ceramics, sand, and papers. The industry classifies polymers into two groups, thermoplastic and thermoset, based on how they react at high temperatures. Thermoplastics are substances that become plastic when heated and harden when cooled, a repeatable process with the same material. Thermoset polymers undergo a permanent change and become set when heated, but cannot be remolded or reheated. The primary polymer materials used include acrylonitrile-butadiene syrene (ABS), polyactic acid (PLA), soft PLA, polyvinyl alcohol (PVA), and polycarbonate (PC).[57] The primary materials used to produce metal AM parts include steels, titanium, and other alloys such as aluminum, nickel, cobalt-chromium, copper, gold, silver, and platinum.[58] Researchers are expanding AM materials and their applications to cement slurries, hydrogels, living cells, and tissues.

ISO/ASTM 52900 lists the approved AM process categories.[59] These processes typically build parts by utilizing either a powder bed (or vat) of material, or by directly depositing material onto a build plate. The approved list includes:

1) **Material extrusion** (known as Fused Deposition Modeling or FDM) is the most common AM polymer process, selectively dispenses material through a nozzle or orifice.[60]

Feeder material typically consists of thermoplastic filament, but can be any viscous liquid or slurry without melting or phase change, i.e., suspensions or hydrogels. [61] FDM systems are comparatively inexpensive and represent the largest number of AM machines produced. FDM applications include modeling, prototyping, investment casts, medical applications, and general production. Advantages include availability of low cost systems, speed, and material variety. Disadvantages include part post-processing, relatively low material deposit accuracy, unsuitable for high production volume, and extreme cost variance from $200 to $500,000.

2) **Material jetting** selectively deposits droplets of build material,[62] using multi-jet print heads, primarily for investment casting. [63] Advantages include the ability to print multiple materials simultaneously. The disadvantage is that material jetting is limited to photopolymers, cured by UV light,[64] and wax like materials.

3) **Binder jetting** selectively deposits a liquid bonding agent to join powder materials.[65] For this process, the powder is *not* the "build material", instead the deposited liquid binder serves as the build material by holding the powder in the desired shape.[66] An advantage is good production volume. Disadvantages include limited materials and some post-processing.

4) **Sheet lamination** bonds sheets of material (papers, metal tapes, and metal foils) to form a part that resembles plywood type construction, before it is cut to the desired shape.[67,68]

5) **Vat photopolymerization (**or Stereolithography - SLA**)** selectively cures a vat of liquid photopolymer layer by layer via light-activated polymerization.[69] Primarily used for high quality models and injection mold casts, its advantages include high resolution, high speed, and a variety of material features such as rigidity, transparency, and strength. Disadvantages include post-process curing (with some finishing), material brittleness over time, high machine cost ($100,000-$500,000), high material cost ($200 per liter), and unsuitable for large parts or high volume production. Advances in vat photopolymerization led to Continuous Liquid Interface Production (CLIP) process, which uses both photo-curing (DLP) and oxygen curing to produce parts more rapidly than traditional SLA.

6) **Powder bed fusion** employs thermal energy to selectively fuse powder bed regions, with unused powder acting as a support structure.[70] Applications include prototyping, low volume production, full production, and electron beam melting (EBM).[71] Advantages include faster, stress-free parts. Disadvantages include a rough sand paper finish, difficulty changing materials, and high machine cost ($1M). Powder bed fusion includes "sintering" processes such as Selective Laser Sintering (SLS), Direct Laser Sintering (DLS), Direct Metal Laser Sintering (DMLS), and Direct Laser Melting (DLM).[72] Sintering advantages include precise detail with a better surface finish, while disadvantages include post-production machining and finishing.

7) **Directed Energy Deposition (DED)** applies thermal energy via laser to melt and fuse metal powder as deposited.[73] An advantage over sintering is that it completely melts the powder. DED also produces functionally graded products since it can simultaneously deposit more than one material.[74] A unique DED application includes repairing parts or tools by adding layers, when used with a 4 or 5 axis motion system to allow deposition on multiple planes.[75]

Future Additive Manufacturing Applications

AM holds promising potential for DoD application beyond simply providing prototypes and spare mechanical parts. Metal, polymer, and ceramic AM techniques could provide the military services with capabilities ranging from printed battle armor and embedded electronics in helmets to the replacement of antennas currently attached to headgear.[76] Strain gauges and other sensors could be embedded in aircraft to provide data on performance and wear.[77] AM can enable the redesign of weapon system components and subsystems to reduce weight, reduce the number of parts, and increase structural performance. Parts will be produced for legacy aircraft without the need to maintain physical drawings and tooling.[78] With the development of new composite polymers, polymer parts may become acceptable replacements for some metal parts.

Like the DoD, industry at large is betting that evolving AM process quality will allow the transition from prototype to production builds. General Electric (GE) made headlines by using metal AM to manufacture a fuel nozzle for its LEAP jet engine. The design reduced the number of components from 20 to one and garnered FAA certification on a critical flight component.[79] Lockheed Martin used metal AM to print space components. In February 2017, the DoD awarded Boeing a 679-million-dollar project to build five F/A-18E Super Hornet aircraft, which will contain more than 150 printed parts.[80] Ford Motor Company has printed well over 500,000 parts to date, saving millions of dollars, but most of these parts are for prototype vehicles.[81] The company envisions future dealerships using 3D printers to create on-demand replacement parts. Early in 2017, Audi established a partnership with German AM manufacturer EOS to expand Audi printing capabilities in prototyping, tooling, and spare parts delivery.[82]

The medical sector offers especially intriguing future AM applications. The fabrication of hearing aids, dental and medical models, surgical guides and instruments, and body implants are just the beginning.[83] Improving surgery success rates by using organ models and eventually printing organs are each within the realm of possible. In August 2015, the FDA approved a layer by layer printed prescription pill made by Aprecia Pharmaceuticals aimed at treating certain types of seizures in epilepsy patients.[84] U.S.-based Organovo, launched its second 3D bio printing product "ExVive Human Kidney Tissue" in September 2016.[85] The FDA is addressing AM design, manufacture, testing, and validation.

Other future applications of AM include home building and electronic circuit design. American construction company (Sunconomy) and Russian 3D printing startup (Apis Cor) teamed to "print" a cozy but livable 400-square-foot house within a day on the outskirts of Moscow in December 2016.[86] NASA is experimenting with "Contour Crafting," to fabricate lunar and Mars settlement infrastructures.[87] In 2016, Israeli company Nano Dimension released the world's first multi-layer circuit board 3D printer - Dragonfly 2020, which prints a circuit board in a matter of hours.[88] German Next Dynamics developed its NexD1 multi-material 3D printer, which prints circuit boards, full-color prints, and flexible materials.[89]

Additional Technology Considerations

The microstructures of metal AM parts must be better understood before gaining the confidence of qualifying bodies common in the defense, aerospace, and automotive industries. Mechanical property testing for metals, tension, compression, bearing, modulus, hardness, fatigue, fracture toughness, and crack growth are necessary to measure material properties in a standardized way. In addition to additively produced parts, testing and assessing the properties of metal feeder powders will further define standards contributing to reliable production across industries. Research on metal AM microstructures is ongoing at the Oak Ridge and Lawrence Livermore National Laboratories as well as several American universities.

Tooling may serve as a point of entry in the metal AM market. GE in 2016 indicated that AM processes will impact 25% of its products by the year 2020.[90] In addition to printed parts, this number includes the tooling made by metal AM machines. While GE is sold on the benefits of metal AM created parts and tooling, other companies may enter the market through tooling. Applying AM to tooling can allow more cautious companies to stake a claim and learn the technology before applying it to production parts.

The AM industry's potential is attracting new Fortune 100 entrants. GE's acquisition of Arcam showed the company's resolve in the metal arena. HP's Jet Fusion printer, released in late 2016, is expected to disrupt the polymer sector. The Jet Fusion leverages HP's ink jet technology to produce high quality parts ten times faster and at half the cost of current AM systems.[91]

Technology Challenges

The ultimate goal for AM is speed, precision, finish, uniform material density, limitless, size, consistent raw materials, material safety and storage, optimization of digital manufacturing, and sufficient industry policy governance. Current challenges to these objectives include product integrity, a lack of industry standards, a need for in-process controls, and ongoing machine-to-machine variability.

2. AM and the Triple Helix – Ensuring Competitive Advantage

The presence in close proximity of top-tier universities, a highly skilled and talented workforce, mature companies, and capitalized investors – all buttressed by strong governmental institutions – together conspire to create the conditions for technological advancement and innovation to occur.[92] Such innovation clusters facilitate the complex interplay between government, industry, and academia that generates the accumulation of knowledge and society's subsequent application of that knowledge to advance a nation's competitive advantage.[93] This interplay and relationship between government, industry, and academia are what scholars refer to as the "Triple Helix."[94] This section will explore the criticality of the Triple Helix to achieving and sustaining a competitive advantage through advanced manufacturing, a critical driver of economic growth. It aims to address five major lines of enquiry: (1) the nature of economic growth and innovation as related to the Triple Helix; (2) manufacturing's importance to economic growth; (3) the U.S. manufacturing industry's current state and its potential for future growth; (4) the role of government, industry, and academia in promoting and sustaining economic growth as related to manufacturing; and (5) recommended policies to increase collaboration between Triple Helix elements and improve the U.S. competitive advantage.

Economic Growth, Innovation, and the Triple Helix

Many factors influence economic growth, such as societal institutions, political stability, rule of law, education, domestic industry competition, technology, innovation, and governmental policies.[95] This suggests that government, industry, and academia all play a role in setting the most favorable conditions for economic growth. More specifically, the Triple Helix describes those government-industry-academia relationships that accelerate the "potential for innovation and economic development in a Knowledge Society" to "generate new institutional and social formats for the production, transfer and application of knowledge."[96]

The successful discovery and application of knowledge before others will give the U.S. a long-term edge in the never-ending competition for military, economic, cultural, and technological dominance against a rival like China. Therefore, it is critical that the U.S. adopt an effective economic and industrial strategy that advances a sound approach to leveraging and exploiting all three elements of the Triple Helix. The fact is the U.S. already possesses a competitive advantage in many areas influenced by the Triple Helix – specifically innovation capacity, business sophistication, strong and sound financial/business institutions, political stability and rule of law, and the higher education/training of workers who participate in a highly efficient labor market. [97] The existence of asymmetries makes a strong case for the Triple Helix to be the centerpiece of U.S. competitive economic strategy.

The Importance of Manufacturing for Innovation-Driven Economic Growth

For a nation to innovate, it must conduct the basic research necessary to create new technologies and subsequently engage in the applied research that enables their commercialization. Engineering, or making things, is a critical requirement of high order technological innovation, because technological breakthroughs manifest in tangible ways services do not. Manufacturing represents 16% of the world's gross domestic product, accounting for several trillion dollars' worth of economic activity.[98] In the U.S. alone, manufacturing comprises 12% of the nation's gross domestic product (GDP) translating to $2.2T in economic output.[99] The multiplier effect of manufacturing is the highest of any other economic sector, with $1.8 added to the economy for every one dollar spent on manufacturing.[100] Further, manufacturing jobs are some of the highest paying in the U.S. economy, with manufacturing workers earning on average nearly $18,000 more per year in pay and benefits than the average worker in all non-agricultural sectors.[101] By some estimates the total value of the manufacturing goods value chain, combined with all manufacturing activities in support of other industries, comes to approximately one third of GDP and employment in the U.S.[102] Given manufacturing's importance to national prosperity, the hemorrhaging of manufacturing capacity from the U.S. to cheap labor countries, particularly China, has caused great concern for many economists who associate a continual decline in median income levels with this phenomenon.[103]

The AM component of the manufacturing industry is a highly-advanced industry segment that uses a combination of computer-aided design and specialized machinery to produce things in ways far different than traditional methods. The potential of AM to bring manufacturing capacity back to the U.S. should be of major interest to government policy makers.

The Current Life Cycle Position of Additive Manufacturing Industry

AM encompasses an innovative and diverse group of industries holding the potential to transform the conception, design, and production of goods in ways not seen since the Industrial Revolution. AM is revolutionary because it enables the design and production of things that are not possible under traditional manufacturing methods. With continual advancements in technology and innovation, many experts predict AM could potentially displace large segments of traditional manufacturing markets, provided economies of scale come to fruition. Timothy Weber, Global Head of Hewlett Packard's 3D Materials and Advanced Applications, has even gone so far as to predict that, "in the future, 3D technology will make manufacturing localized and customized" to the point that "large container ships transporting goods around the world will be a thing of the past."[104] Such an outcome would be of tremendous benefit to the U.S., because its heavy investment in AM technologies make it well positioned to reconstitute a large part of its domestic manufacturing capacity lost to China and elsewhere since 2000.

The Triple Helix and Overcoming the Valley of Death

The so-called "valley of death" refers to the situation in which technological progress and innovation evaporate because "development becomes too applied [commercial-oriented] for research funding and not specific enough for funding by business."[105] The existence of the valley of death is a major reason government, in conjunction with industry, must actively work to ensure promising technology and innovation survives. Otherwise society will undeniably lose out on important technological advancement.

A recent U.S. example of successful Triple Helix is the Energy Star program, which spurred innovation and economic growth through government regulations and economic incentives to encourage increased energy efficiency in the design of computers, computer servers, household appliances, heating and cooling systems, electronics, and lighting.[106] The mission of Energy Star is to "identify and promote energy-efficient products and buildings in order to reduce energy consumption, improve energy security, and reduce pollution through the voluntary labeling of or other forms of communication about products and buildings that meet the highest energy efficiency standards."[107] It proved to be one of the most successful governmental innovation programs of all time, resulting in the creation and economic viability of technologies that have given American industry and families more than $295B in energy savings, while generating billions more in economic activity for the U.S. economy.[108]

Policy Recommendations

Implementing the following policy recommendations will foster conditions necessary for idea creation, knowledge discovery, technological advancement, innovation, and rapid commercialization of the same. The government should become a sophisticated buyer by giving industry and academia major challenges or technological problems to overcome and, in the case of industry, be willing to compensate it for assuming risk. Regarding AM specifically, government should fund and encourage further research and development so AM progresses to the point that economies of scale allow it to displace many traditional forms of manufacturing that are cheaper to offshore or outsource abroad. This includes resourcing US national labs that are engaged in basic research, as well as public and private universities engaged in both basic and applied research aimed at commercializing new technology.

In public-private partnership arrangements that advance the state of AM, structure royalty awards and commercialization incentives so that innovators and industry reap the majority of future profits, making AM more economically viable. Rewarding long-term capital investment tied to performance may solidify long-term commitment and drive greater innovation beyond that realized during the short term.

Continue supporting public and private partnerships, such as Manufacturing USA, with targeted investments and access to research assets that prevent promising smaller firms and innovators from falling victim to the valley of death. Explore the expansion of government-backed venture capital initiatives as another way to achieve this. The government's successful investment and sponsorship of new and emerging technologies to advance technology commercialization and national security are well-documented.[109]

Offer awards and prizes with financial incentives and temporary exclusive use of intellectual property for commercialization of technology developed with governmental support. Implementing international IP enforcement to prevent overseas practice with little or no repercussion could further entice commercialization.

Reduce the corporate tax rate for the manufacturing sector and offer R&D tax incentives.

With human capital being a critical factor of productivity and competitive advantage, implement targeted immigration policies that actively recruit the world's best and brightest, as we continue to invest in Americans at home.

Conclusion

National competitive advantage is predicated on a multitude of factors that include dense innovation clusters of top-tier universities, educated and talented workers, mature companies, and resource-heavy investors, all collaborating under the aegis of a government comprised of strong institutions that facilitate a dynamic academic and business environment. Since manufacturing is the chief sector in the economy involved in the production of goods, better technology and innovation in the manufacturing sector will lead to greater economic growth. This in turn will help ensure resources necessary to provide for national security. Government policy, that facilitates and incentivizes close cooperation between industry and academia to achieve government-driven security and economic goals that increase national power, will prove critical to improving America's global competitive advantage vis-a-vis its adversaries.

3. DoD Supply Chain Management

AM Impact on DoD

In the late twentieth century, globalization of supply chains became the trend and offshoring efforts became the norm, as production moved from western countries to the far east. As the nation's industrial base set sail for Asia, so too did the security of the DoD supply chain. But the tide is turning and domestic manufacturing is indeed making its resurgence, and as a result, will shore up DoD supply chain vulnerabilities. Anticipated technology advancements will make AM a disruptive entrant to the future DoD supply chain. It will introduce game-changing results, including the impact it creates on DoD's strategy to combat diminishing sources of manufacturing and supply, reduce labor and inventory costs tied to managing the supply chain, and sustain deployed forces.

AM Today

The DoD has become an early adopter of 3D technology, has developed detailed implementation plans to ensure a thorough and well-coordinated effort, and to date has demonstrated significant success in its initial applications. A prime example among many is the U.S. Army's UH-60 Black Hawk and AH-64 Apache helicopters, which contain 3D printed inlet swirl frames on their engines.[110] Employing this technology reduced the final product from 147 aggregated parts to 25, and slashed 926 steps from the production process.[111] According to the Army's Manufacturing Technology office, 3D manufacturing's future will yield, "alternate weapon component manufacturing methods, increasing (the) supply base and supplier competition."[112]

Potential Opportunities

In the face of shrinking post-Cold War budgets, volatile funding, and the drought of modernization and procurement dollars, the U.S. military spent the better part of the last two decades resolving how to modernize and extend the service life of existing weapon systems. As platforms age, resourcing spare parts becomes an exponentially increasing challenge. AM reveals itself as a viable strategy to counter Diminishing Manufacturing Sources and Materiel Shortages (DMSMS) challenges. The DoD strategy of diversifying its supplier base entails keeping expansive production capacity on retainer, constituting both a sluggish and expensive reliance. AM holds the keys to an alternate fate. Utilizing a network where a vast array of unique parts can be quickly produced by a scant number of suppliers opens the future to rapid, less expensive parts production in small numbers, generating positive readiness impacts.

The DoD repair cycle contains three major nodes; the end user, the depot maintenance repair facility, and the transportation between the two. As end users consume parts on one end, they simultaneously ship parts back to the depot for repair, and the depot ships repaired parts back to the end user in the field. Conceivably, with continued technology advancements, this entire system (including facilities, equipment, manpower, suppliers, and spare parts) could eliminate some functions, and drastically modify others. Presuming 3D printing costs continue declining, and transportation costs continue increasing, a future where parts are simply printed on site, vice inducted into the repair cycle, could eventually become a cheaper and more effective alternative. Drastic reductions in transportation costs, workforce size, and spare parts inventories, all feasible realities with the adoption of AM, can create significant DoD savings.

The DoD's large scale deployment model requires large spare part inventories and equipment to be postured, deployed, and replenished in forward operating locations. Initial deployments may entail numerous ships or aircraft for transporting assets, real estate to store the items, and significant resources to maintain, secure, and replenish depleted assets. AM presents opportunity to decrease these requirements and identify efficiencies. Reducing deployed inventories may reduce costs, but may jeopardize readiness. However, AM offsets this risk by introducing a deployed manufacturing capability which enables deployed forces to create parts or tools on demand, satisfying mission requirements while alleviating expensive logistics footprints.

Potential Vulnerabilities

An AM-based sustainment strategy contains inherent risks based on its susceptibility to enemy targeting. The most feasible scenario for AM implementation in the future involves using a centralized digital library as a single authorized repository for digital blueprints. As a critical vulnerability, the enemy would strategically target this critical capability for attack. Successfully disrupting the U.S.' logistical tail by denying digital library access would degrade power projection and potentially cripple globally deployed forces. Additionally, the enemy could manipulate CAD file drawings causing part failure, destruction, or even death during combat operations. The digital parts and printing infrastructure will serve as a critical warfighting node that enemies will undoubtedly target before and during future conflict. As a primary sustainment objective, the U.S. must prudently secure the digital library during both peacetime and war.

Policy Recommendations

The DoD must institute three policies to most effectively integrate AM into its future sustainment strategy. First, DoD should assume a strategy of "just in time" printing for long-lead and hard-to-procure parts. By adopting this as a primary sustainment strategy, sustainment operations could become cheaper and faster, improving both supply chain efficiency and effectiveness. Second, DoD should consider making 3D printing the future centerpiece of its mobility posture. Whether on a ship or a forward deployed location, the speed at which 3D printers can produce tools and parts may prove cheaper while also generating readiness improvements. Finally, any effort to advance AM must, without compromise, encompass robust cyber security initiatives. With AM's future likely to include field units printing parts from drawings contained in a centralized digital library, protecting that repository must be a top priority. In an armed conflict, enemy efforts could effectively deny access to, or worse, manipulate digital drawings.

Unlike traditional manufacturing, which utilizes casts and molds to ensure production uniformity, product consistency is not inherent in AM. Part certification in major DoD programs, especially aviation, such as airworthiness certificates, are crucial to maintaining operational readiness. If AM stands a chance at becoming a viable implement, the industry must attain product consistency to achieve requisite certifications. Four focus areas to achieve standardized production include printer certification, people certification, process certification, and digital library security. Establishing standardized, certifiable, and secure processes, equipment, operators, and document libraries will lead to repeatable and predictable parts consistency, maximizing the efficiency, effectiveness, responsiveness, and security of the DoD supply chain.

Conclusion

Recent AM advances have made it the next potential disruptive technology to affect the DoD. As it continues progressing, the DoD has an opportunity to leverage AM as a hedging strategy against supply chain vulnerabilities. By investing in industry innovation, DoD will posture itself to maximize the enduring benefits additive manufacturing offers. This strategy provides benefits beyond the base supply chain, and presents opportunities to counter DMSMS issues, reinvent the repair cycle, and create premier opportunities for warfighting efficiency, effectiveness, and innovative capabilities. However, the same benefits also present vulnerabilities to certification and standardization. By implementing the right policies and certifications, AM is poised to become the disruptive technology the DoD seeks to make new leaps toward the next generation in warfighter sustainment and capability.

4. "Additive" Manufacturing Workforce

A significant challenge for the AM industry, as it disrupts traditional manufacturing, is developing a capable, adaptable, and agile workforce. Workforce requirements include technically skilled AM equipment and machinery operators, maintainers, research engineers to advance the industry, and managers who can integrate the technology into manufacturing processes. Although in existence for over 30 years, AM technology only recently took off, with more than two thirds of U.S. manufacturers now using some form of AM to produce prototypes or final parts in industries ranging from biomedical to automotive to aerospace.[113] With AM growth outpacing its workforce, the sector struggles to meet rising demand for educated and skilled workers in the design, development, and production processes.[114] Without a cultural change to begin thinking differently about the role of advanced technology in manufacturing today, the U.S. will be left behind as a global leader in technological innovation. Consequently, the U.S. economy will lose out on the industry's potential employment, production, and trade benefits.

One of the most heavily debated issues in the AM industry today is the notion of a "skills gap," leading to extensive research by many respected firms. According to a Deloitte survey of the industry, "nine out of ten manufacturers today are struggling to find skilled and educated workers needed to operate 3D machinery and to conduct R&D."[115] The manufacturing industry recognizes that a lack of a talented workforce in AM is holding the industry back, and preventing it from capitalizing on its full potential. This problem will likely grow worse if present trends continue. The Deloitte study reported on several factors which impinge on the industry's search for skilled workers. One factor is a society-wide problem of an aging population, meaning more people are retiring from the workforce than entering it.[116] Other important factors, according to the Deloitte study, include a negative perception of employment in manufacturing among the younger generation, the lack of STEM education across all levels of education, and the decline of technical programs in primary and secondary schools.[117] To more fully realize the potential of AM, the government, industries, and educational institutions must focus on preparing and developing a capable and skilled AM workforce.

Another challenge facing AM today is how to prepare a workforce that can serve the needs of the industry as it moves in new directions. This reflects a broader opportunity for the U.S. to gear its education system toward serving the needs of the society, and to remain competitive in an increasingly global economic environment. In 2011, President Obama launched the Advanced Manufacturing Partnership (AMP), "a national effort to bring together industry, universities, and the federal government to invest in emerging technologies that will create high quality manufacturing jobs and enhance U.S. global competitiveness."[118] The following year, the Obama administration established a public-private institute, the National Additive Manufacturing Innovation Institute (currently known as America Makes) in Youngstown, Ohio, to include manufacturing firms, universities, community colleges and nonprofit organizations from the Ohio-Pennsylvania-West Virginia "Tech Belt."[119] This consortium comprises one of up to 15 manufacturing innovation institutes around the country, to which the Obama administration committed up to $1B, to be matched with funding from the private sector.[120]

In assessing government efforts to address these concerns, one missing element is effective worker pipeline development, as well as consistency in terms of quality among the different models. Technological advances in manufacturing alleviated the need for large numbers of employees packaging and processing products, but instead created a need for technicians who understand programming and design. The steel production plant in Pittsburgh, PA provides a great example of this, where large volumes of steel are produced and transported throughout the plant with mainly machines and computers. It appears academia has yet to keep up with this pace. Few degree programs in the areas of ADMAN and AM exist in universities. STEM education is at best being *suggested* within the U.S. K-12 public school system, as opposed to mandated. Universities and local public school districts located in places such as Raleigh, NC and Pittsburgh tend to benefit from workforce training due to the local manufacturing industries. The Federal Government's efforts do not adequately address academic institutions located in rural parts of the U.S. where no industries exist. Early in our nation's history, lawmakers passed the 10th Amendment to the Constitution which is the basis for making education a function of the states.[121] The respective community administers and finances each community along with that district's state government.[122] State funding goes primarily to public institutions, while federal funding goes to students at public, private and for-profit colleges, and to researchers at public and private universities.[123] At best, state managed colleges and schools receive minimal Federal Government funds (title 10). If states do not incentivize industries to locate in these areas, and the Federal Government does not constitutionally own these educational systems; these populations will not receive potential Federal funding that could augment state support and more optimally resource STEM/workforce training.

Policy Recommendations

Pipeline development is primarily a function of the public-school system, and cannot be managed solely by industry and government. By the time prospects reach industry's attention, significant skills gaps and other major irreversible damages exist. Skill development should start in early stages through education managed by the states, given they are constitutionally responsible for education. However, state systems have proven insufficient and require federal support. This support should come in the form of federal policy and incentives to promote curriculum reform and address the pipeline at the earliest opportunities available. Federal policy and incentives should influence states to identify prospects at an earlier age, rather than in high school or college. Some students drop out before reaching high school, and those that don't tend to perceive and associate manufacturing with negative public images of "dirty, declining, and low pay."[124] The K-12 public school system inadequately informs young students on manufacturing career opportunities and fails to impart the skills required by the ADMAN industry. ADMAN involves all skills falling under STEM, yet many school systems do not allow students access to STEM courses. Education professionals normally attribute this to overly crowded schedules, which places students in positions to choose certain subjects over others. This significantly contributes to poor exposure and generates very few talented, high-skilled workers who seriously consider manufacturing careers.

Conclusion

The U.S. remains at the forefront of technical innovation, a position which gave the country a strong, robust economy for decades. But in an ever changing, increasingly competitive world, the U.S. cannot afford to lose its economic lead. Rising powers, such as China and India, consistently pour money into R&D of new technologies. Moreover, they devote significant portions of their national budgets toward education, preparing their young people to lead in technologically advanced careers. The U.S. cannot hope to match that sort of investment, for a host of reasons. Innovation comes from the bottom up, and the AM industry is just one of several new industries which promise to keep the U.S. economy moving forward and competitive. Providing the manufacturing industry with a well-prepared workforce is ultimately a national security matter, as it is that competitiveness and economic strength, that underwrites the remaining elements of national power and secures the U.S. as the world's leader.

5. Security Implications

3D printing, as with many emerging technologies, must balance societal benefits with new complex security challenges. The age of globalization, cyber threats, asymmetric non-state actors, and the rise of near-peer powers compounds these challenges. It is critical to understand the threats emanating from the proliferation of additive manufacturing (AM) technology before implementing mitigation strategies. AM related regulation and policy must be implemented before this disruptive technology escapes the influence of the U.S. and its allies.

3D Printing as a Combat Multiplier

AM increases proliferation across the weapons spectrum from personal firearms to components in nuclear systems. Texas company Defense Distributed already sells printers and software models that enable individuals to produce controlled firearm components,[125] and is known for creating "the world's first 3D printed pistol."[126] Additionally, anyone can find 3D printable designs online[127] that complement technologies already capable of printing military grade explosives.[128] Advanced missiles will likely proliferate among hostile entities with AM capabilities. Major companies, like Raytheon, already boasts that "nearly every component" of a guided missile they produce can be created using AM, and they expect these weapons to be produced on future battlefields.[129] Advanced anti-air and anti-armor missiles will provide enemies with an increased lethality not yet seen in post 9/11 conflict zones. AM can even produce centrifuge components to enrich uranium for nuclear weapons.[130] Additionally, AM will render many current tools used to identify unlawful nuclear activity obsolete;[131] as a $1M machine with the right design files is now capable of producing components, previously impossible with even the best technology and highest skilled technicians.[132]

AM threat applications are frightening and varied. Hostile actors can extend the lifecycle of U.S. built equipment, either provided or stolen, without U.S. approval via a clever combination of reverse engineering and AM. From Iran's continued use of American F-14s provided under the Shah's regime, to armored vehicles stolen from the Iraqi military by ISIS, AM potentially makes these weapons a part of their respective arsenals for decades to come. AM direct threats will include "lone wolf" actors in the U.S. with an ability to produce weapons and explosives in concealed environments. This inability to detect terrorist attacks within the homeland at the planning or resourcing phase will seriously hinder law enforcement chances for successful interdiction of terrorist plots prior to their execution. Terrorist organizations also benefit tremendously from potential AM applications. For example, Hezbollah's next Israeli conflict may demonstrate an increased ability to maintain consistent rocket fire rates into Israeli villages, by using additive machines to print rocket components and circumvent Israeli disruptions of supply routes into southern Lebanon.

AM also provides near-peers tools to counter U.S. strategic objectives. Russian irregular forces in Eastern Europe, similar to Crimea and Ukraine, will have greater weapons access and increased freedom-of-movement as they infiltrate neighboring nations with little observable logistics tail. This epitomizes the Gerasimov doctrine of indigenous sympathetic fighters, "supplemented by military means of a concealed character."[133] An emerging power like China, who already demonstrated the ability to 3D print entire buildings,[134] could feasibly use AM to undermine U.S. interests by rapidly printing aircraft hangers, command posts, and other structures on artificially enlarged islands in the South China Sea. 3D printing soars on a trajectory to join unmanned vehicles and cyber warfare as the next great equalizer to challenge military global superiority.

Cyber Threats

AM users typically use Information Technology (IT) systems for administrative activities and Operational Technology (OT) systems for production, which includes Industrial Control Systems (ICS). As illustrated in Appendix A, potential cyber risks dot the OT segment. In addition to digital threats, people often create the greatest source of system weakness, either through open subversion or unwittingly by poorly executing cyber hygiene. Consequently, cyber vulnerabilities allow the possibility of numerous malicious activities to occur including: theft of intellectual property, sabotage of supply chains, and directed denial of service attacks (see Appendix B for additional cybersecurity concerns).

To mitigate cybersecurity threats, several companies opt to entirely disconnect production machines from the internet.[135] This method complicates machine and process optimization, as devices may not receive timely security patches and upgrades. To compensate, IT specialists manually upload files from thumb drives, potentially complicating version control. This may impair efficiency and productivity, while potentially impacting quality control and output standardization. Moreover, the machines may be at greater risk if reconnected to the internet without proper updates. File Transfer Protocol (FTP) servers, commonly used by 3D printer operators, are an insecure technology that makes servers vulnerable targets. In addition, most digital model data files use an unencrypted file format developed nearly 30 years ago.

The effects of cybersecurity breeches are extremely common and costly. According to an Federal Bureau of Investigation (FBI) survey of 165 private companies, "half said they were victims of economic espionage or trade secret theft — 95% of those cases involved individuals associated with the Chinese government."[136] In addition to IP theft, a recent National Intelligence Estimate reported the "increasing role of international companies and foreign individuals in U.S. IT supply chains and services will increase the potential for persistent, stealthy subversions."[137] Additional cyber threats and actors, specific to the manufacturing sector, can be found in Appendix C. Consequences of cyber-attacks are also expensive, with recovery costs estimated to be $2T globally by 2019 and the average cybercrime costing a U.S. company $15M.[138]

Autarky & Export Controls

Most nations desire autarky in their defense industry to ensure foreign entities cannot limit the security autonomy states naturally desire. Many argue that despite desiring autarky, states cannot possibly maintain autarkic defense production, while simultaneously fielding effective defense systems. Potential cost reductions and performance gains from leveraging the international economy are too great to ignore; since the 1970s, even the U.S. experienced rising globalization in defense production. In short, autarky is desirable but impractical due to globalized industry requirements.[139] A countervailing view is that the U.S. made a strategic decision to sacrifice autarky, to gain influence over other states by linking them to the U.S. DIB.

This encourages burden sharing while limiting the rise of international competition. In this view, autarky works counter to U.S. security goals by limiting control over DIB supply chains.[140]

As 3D printing transitions to large-scale commercialization, one key consideration is whether it is possible and/or desirable for the U.S. to maintain autarky in 3D printing. Since 3D printing is an enabling technology, rather than a product, many potential benefits from abandoning autarky do not apply, thus autarky in AM is desirable. Unfortunately, the fact that many leading AM companies are located outside the U.S., and that even U.S.-based AM leaders are multinational corporations, make it impractical for the U.S. to maintain pure autarky. Never-the-less, diffusion of AM technology to a wide array of countries, particularly Western allies, make it unlikely that a potential adversary could effectively deny U.S. access to AM.

Another consideration is whether the rise of AM technologies might impact the broader concern of autarky in the larger DIB. Here, AM technologies may reduce global DIB risks by providing an alternative source of components should traditional vendors be unable or unwilling to supply U.S. needs in a crisis. In essence, the U.S. can improve national security by maintaining autarky benefits in the broader DIB, while reducing risks from relying on international suppliers.

Policy Recommendations

The U.S. must lead international efforts to limit access to printers capable of producing missile and reactor components. The U.S. can accomplish this through export controls and international tracking measures, similar to those currently used in nuclear counter-proliferation efforts. With AM making personal firearms and explosives more accessible, American intelligence and law enforcement officials should begin tracking print materials, such as explosive metal powders, in the same manner as fertilizers to minimize the threat of terrorist weapon production within the U.S.

Additionally, the U.S. must also implement cybersecurity changes. Currently, the DHS-governed "critical manufacturing" sector focuses on traditional, subtractive manufacturing in support of defense, energy, and transportation sectors,[141] while neglecting AM. Adopting cybersecurity best practices, and incorporating additive activities supporting DOD into the nation's designated critical infrastructure sectors, can mitigate IP risks and other industry vulnerabilities. Regulation should also harden primary targets and prevent compromised commodities from entering the additive supply chain. Finally, personnel in any additive position connected to either the DoD or any military application should be regularly trained on protective cyber practices.

Regarding autarky, the U.S. should focus AM investments on key areas: education, immigration, technical and legal standards development, alternative models for offsets and supply chain management, and funding development for defense-unique requirements. Although the U.S. will not likely achieve pure autarky in the AM industry, leveraging capabilities of U.S.- and allied-based firms will likely prevent adversaries from limiting DoD access to AM. Furthermore, incentivizing broad domestic AM commercialization may mitigate globalization risks to the DIB, by facilitating alternatives to foreign manufacturing and encouraging "reshoring" to the U.S.

Conclusion

The plethora of AM security challenges seems daunting with threats emerging across a broad spectrum. Threats range from a local terrorist printing a gun, to cyber-attacks that cripple the military supply chain, nuclear proliferation, and the loss of sovereignty and IP inherent with the erosion of American autarky. However, a deliberate effort to identify the variety of complex threats now, while AM remains in its developing stage, will enable the U.S. to develop and implement sound policies that can protect our national interests through the ADMAN revolution.

CONCLUSION

Additive manufacturing has arrived. With continued growth expected over the next decade and beyond, the U.S. must embrace this new technology and seize momentum in guiding AM innovation to achieve national security objectives and global economic leadership. AM can increase lethality of deployed forces while simultaneously reducing the American military footprint abroad (and associated costs), improve supply chain management and responsiveness, and provide economic stimulus to the nation. However, these benefits will not happen without taking action. The government is responsible for protecting American people and businesses from nefarious uses of 3D printing that range from weapons proliferation and cyber-attack avenues to IP theft and lost market shares to economic challengers. However, policies must not be overly restrictive; balancing security concerns while still fostering growth. The federal government can implement several key initiatives to set conditions that allow our open economic system to allow for U.S. dominance in this disruptive and expanding sector of manufacturing.

A key to gaining an American competitive advantage is nurturing innovation within the U.S., a function in which the triple-helix plays an integral role. The federal government must foster synergy between academia, industry, and government. This vital step in the development of innovation clusters will facilitate growth for extended periods; the most common example of which is "Silicon Valley" in California. Potential government steps include: a longer-term commitment to the already established innovation institutes similar to Britain's "catapult" model, funding shifts from basic research to AM specific functionality, and bolstering fledgling innovation city-states that demonstrate great economic potential through increased federal commitment in the area. This should include increased spending on regional infrastructure, which maximizes economic potential in targeted areas and adds a multiplier effect by tying successful cities to broader regions; bringing greater numbers of schools, firms, and potential employees into that cycle of prosperity. As successful innovation clusters link through physical and technological means, the benefits become distributed nationally.

The government could also restructure corporate tax codes to incentivize corporations to stay in, or return to, the U.S. Incentives that provide financial relief to companies willing to assume innovation investment risks and partner with government, will increase the number of firms partnering with government and allow for either a greater volume of innovation clusters across the country, or at minimum, a similar number of clusters operating at a much greater capacity for wealth and idea generation.

The military plays a significant role in sparking AM innovation due to its large percentage of the federal discretionary budget, coupled with the civilian applications of advancements in AM. This enables the DoD to work closely with companies on innovation; marrying enhanced warfighter capabilities and high returns on investments. For example, utilizing 3D printing to reduce the forward-deployed logistical tail in the form of fewer warehouses, fewer transportation requirements, and faster delivery creates exponential cost savings while enhancing readiness. An open understanding of the positive symbiotic relationship DoD and industry can achieve if they work on AM innovation can lead to consistent positive results for both parties, while increasing trust between DoD and the DIB to levels unseen since the end of the Cold War.

The fight for AM supremacy will be a microcosm for the fight for global military and economic dominance for the remainder of the next two decades or more. America's rise, or fall, in 3D printing will provide a key indicator for America's rising or declining status among global powers. The problem has been identified, the methods to achieve success understood; all that remains is the hardest challenge-committing and executing to achieve U.S. AM industry dominance.

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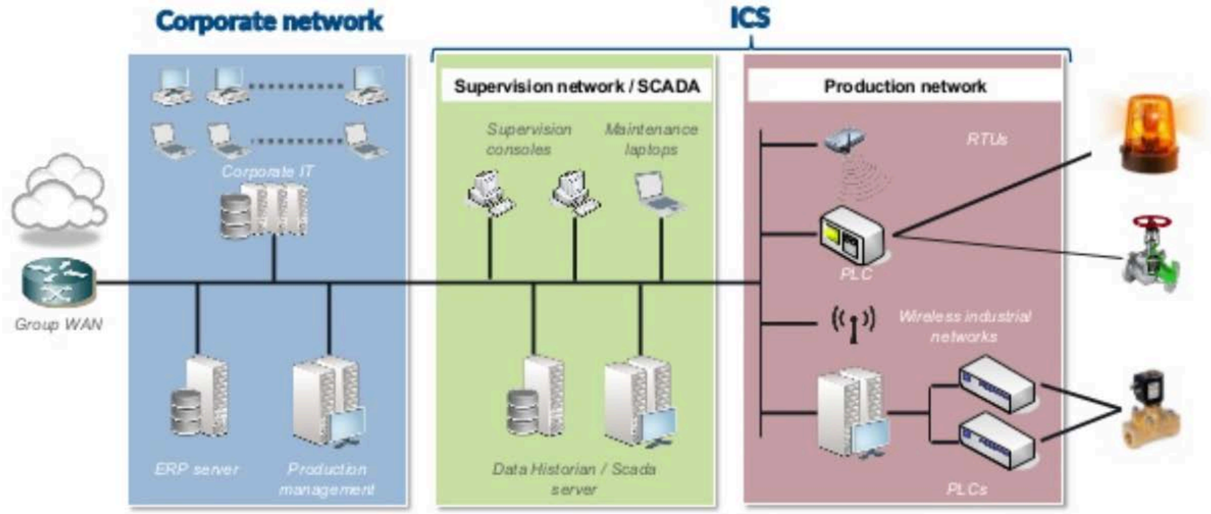
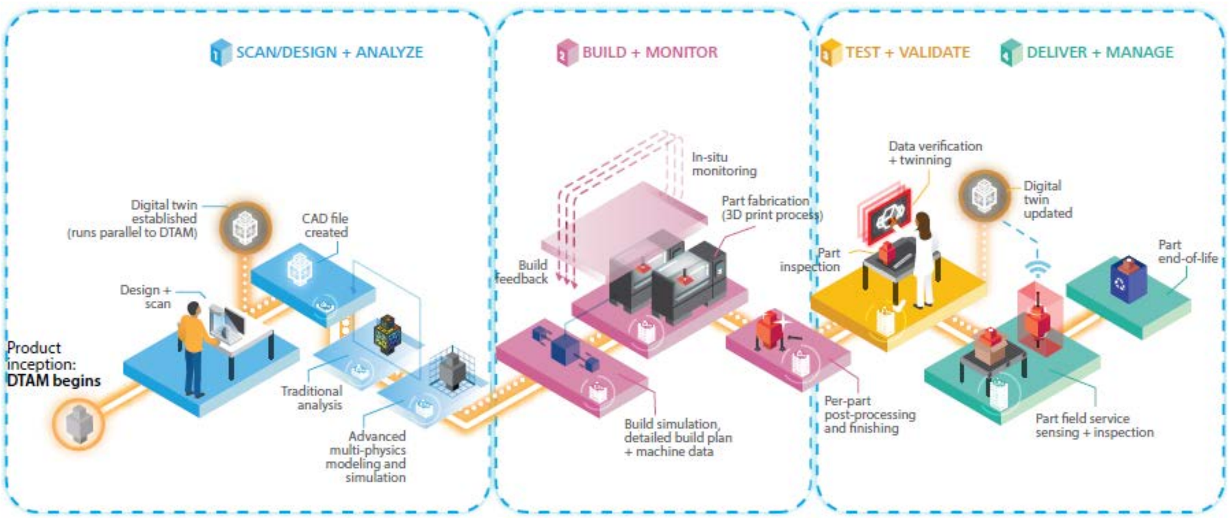
Appendix A (IT/ ICS Diagram & Areas of Cyber Risk)[142,143]





Appendix B (Cybersecurity Concerns & Impacts)[144]

AM-SPECIFIC CYBERSECURITY CONCERNS	POTENTIAL IMPACTS
Design files stolen	• Theft of IP or strategic plans • Reputation damage
Design files changed to build flaws in parts	• Destruction of critical infrastructure • Reputation damage • Threats to life/safety
Unauthorized objects printed	• Theft of IP or strategic plans (counterfeiting) • Reputation damage
Altering toolpath to deposit materials incorrectly	• Destruction of critical infrastructure • Reputation damage • Threats to life/safety
Printers taken offline	• Business disruption
IP-protected objects printed without payment or permission	• Theft of IP or strategic plans (counterfeiting) • Financial theft
Dangerous or illegal objects printed (e.g., weapons)	• Threats to life/safety
Digital twin hacked (e.g., to compromise maintenance)	• Destruction of critical infrastructure • Business disruption • Threats to life/safety
Digital thread hacked (e.g., to affect quality control)	• Reputation damage • Threats to life/safety

Appendix C (Cyber Threats to Manufacturing)[145]

Impacts / Actors	Financial theft/fraud	Theft of IP or strategic plans	Business disruption	Destruction of critical infra-structure	Reputation damage	Threats to life/safety	Regulatory
Organized criminals	Very high	Very high	High	High	Moderate	Very high	Low
Hactivists	Low	High	Very high	High	Very high	Low	High
Nation-states	Low	Very high	High	High	High	High	Low
Insiders/ partners	Very high	Very high	Very high	Low	Very high	Moderate	Moderate
Competi-tors	Low	Very high	High	Low	High	Moderate	Moderate
Skilled individual hackers	Very high	High	Moderate	Moderate	Moderate	High	Moderate

KEY ■ Very high ■ High ■ Moderate ■ Low

Endnotes

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