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Additive Manufacturing

A Guide for Policymakers

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Executive Summary

Additive manufacturing, also known as "3D printing," is a fast-growing technology that is transforming production in a wide range of applications. The United States is a leader in additive manufacturing research and adoption, which could bring significant future benefits to U.S. companies and consumers. However, the technology carries unique risks related to information assurance and intellectual property protection that require attention.

Additive Manufacturing Defined

What Is Additive Manufacturing?

Additive manufacturing is frequently referred to as a "disruptive" technology and a part of the Fourth Industrial Revolution, and often conjures up images of a future that is utopian or dystopian, depending on one's individual outlook. The reality to date, however, is much less fantastical: the technology is not especially new, and as a departure from existing methods of manufacturing its implementation has been more linear than volatile. With that in mind, the potential impact of additive manufacturing should not be underestimated. As with artificial intelligence/machine learning and cloud computing, the "revolutionary" potential of additive manufacturing is also being driven by developments in other fields, which are turning things that the technology "could" do into things it "can" do.

So, what exactly is additive manufacturing? At the core, it is just another manufacturing process. According to the National Institute of Standards and Technology (NIST), additive manufacturing is defined as "the process of joining materials to make objects from three-dimensional (3D) models layer by layer as opposed to subtractive methods that remove materials."[1] In this sense, one can imagine subtractive manufacturing processes as straightforward evolutions of the same process Michelangelo

[1] Douglas S. Thomas and Stanley W. Gilbert, "Costs and Cost Effectiveness of Additive Manufacturing: A Literature Review and Discussion," NIST Special Publication 1176, December 2014, http://nvlpubs.nist.gov/nistpubs/SpecialPublications /NIST.SP.1176.pdf.

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used in sculpting David: the final form is created by removing excess material. Additive manufacturing is the opposite: raw material is built up, layer by layer, to create the final product. Like milling and stamping, it is a means of shaping raw materials into designs necessary for them to perform a desired function, often within the context of a broader mechanical system.

Where Does Additive Manufacturing Fit in the Scheme of Manufacturing?

Additive manufacturing offers a number of key advantages over subtractive manufacturing in specific contexts. According to *The Economics of 3D Printing*, the two most important advantages of additive are the ability to manufacture complex geometries and the ability to create highly customized or differentiated products in very low volume.[2] The first of these addresses the number of ways that additive manufacturing (AM) allow the manufacture of structures that are outside the ability of traditional manufacturing. For example, AM can create objects within objects and internal channels or cavities within objects.[3] This has applications ranging from creating custom hearing aids to lighter, more efficient turbine blades,[4] to building complex structures-within-structures like encased sets of gears.[5] Similarly, the customizability of AM-created products makes them ideal for rapid prototyping, as discussed below, shortening the time it takes to move a product from the design stage to mass production.

Certain features of AM also make it ideal for maintenance applications. AM allows extensive customization and a single printing unit can produce a huge variety of designs with limited capital investment relative to traditional manufacturing. This makes it easier to prepare for a wide range of contingencies when storage space is at a premium (such as in space or on the high seas) and can allow for the reproduction of hard-to-find parts at lower costs. This is good news for the U.S. military, and could help bring needed specialty equipment and repairs to the warfighter faster and more reliably. The Army has already used the technology for printing the Rapid Additively Manufactured Ballistics Ordnance (RAMBO) grenade launcher,[6] while the Navy was able to design and print a proof-of-concept submersible in less than four weeks.[7] (A hull alone normally would take three to five months to manufacture.) It is also good news for fans of antique cars, potentially making it less costly to acquire high-quality replacement parts long after the original manufacturer stops production.

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[2] Martin Baumers, Matthias Holweg, and Jonathan Rowley, *The economics of 3D Printing: A total cost perspective*, January 2016, https://www.sbs.ox.ac.uk/sites/default/files/research-projects/3DP-RDM_report.pdf.
[3] Hannah Bensoussan, "Benefits of 3D Printing: Impossible Designs and Internal Channels," *Sculpteo*, January 18, 2017, https://www.sculpteo.com/blog/2017/01/18/3d-printing-benefits-impossible-designs-and-internal-channels/.
[4] Ursus Krüger, "Interview: From Particles to Products," *Pictures of the Future*, Siemens, October 1, 2014, https://www.siemens.com/innovation/en/home/pictures-of-the-future/industry-and-automation/additive-manufacturing-interview-ursus-krueger.html.
[5] Stephen Chadwick, "Additive Value," *Manufacturing Today*, Europe Issue 133 (October 2016), http://www.manufacturing-today-europe.com/2016/10/13/additive-value/.
[6] Kyle Mizokami, "The U.S. Army 3D-Printed a Grenade Launcher and Called It R.A.M.B.O.," *Popular Mechanics,* March 8, 2017, http://www.popularmechanics.com/military/weapons/advice/a25592/the-us-army-3d-printed-a-grenade-launcher-it-calls-rambo/.
[7] Andrew Liptak, "The US Navy 3D printed a concept submersible in four weeks," *The Verge*, July 29, 2017, https://www.theverge.com/2017/7/29/16062608/us-navy-3d-printing-submersible-manufacturing-military.

This last point highlights another advantage of additive manufacturing, which comes in the form of precision: a single 3D-printed product does not have to account for the tolerances of individual components made on different machines at different facilities. Moreover, so long as inputs are tightly controlled and monitored, AM output is very consistent. This is a major benefit in aerospace, where the technology is rapidly gaining a foothold in the manufacture of engine parts. For example, GE used the technology in the redesign of its LEAP jet engine nozzle, turning 18 parts into a single integrated component with decreased weight and improved performance.[8]

Finally, additive manufacturing enhances other types of manufacturing in forms like support, prototyping, and creating casts. For example, one process being used in the aerospace industry is to create "hybrid printers" by combining printers with computer numeric control (CNC) machines.[9] These machines can create uniform finished surfaces on printed parts. In another example, 3D printing is making the rapid prototyping of printed circuit boards (PCBs) much faster by allowing companies to do their prototyping in-house rather than by an overseas supplier.[10] This has added security benefits for companies worried about sharing sensitive IP, and especially for those in the defense industry working with sensitive information.

Limitations of Additive Manufacturing

Additive manufacturing is not likely to supplant traditional manufacturing for a variety of reasons. For one, the technology does not currently scale well, and conventional manufacturing enjoys a significant cost advantage in high-volume manufacturing. At present, AM's cost and complexity will also make it uncompetitive in the production of very large parts or very simple parts, as well as parts that are currently stamped or made on simple CNC machines. Essentially, printing a large part requires building up a large amount of material. In many such cases, it is simply easier to start with a large amount of material and machine it down.

[8] PwC, "Five Ways 3-D printing is changing manufacturing," April 30, 2017, http://usblogs.pwc.com/emerging-technology/5-ways-3d-printing-revolutionizes-manufacturing/.

[9] Jeff Kerns, "Aerospace Opportunities Demand Quick Resolution to 3D-Printing Issues," *MachineDesign,* April 20, 2017, http://www.machinedesign.com/3d-printing/aerospace-opportunities-demand-quick-resolution-3d-printing-issues.

[10] Simon Fried, "3D Printing Shortens PCB Prototyping Cycle," *ECN Magazine,* October 9, 2017, https://www.ecnmag.com/article/2017/10/3d-printing-shortens-pcb-prototyping-cycle.

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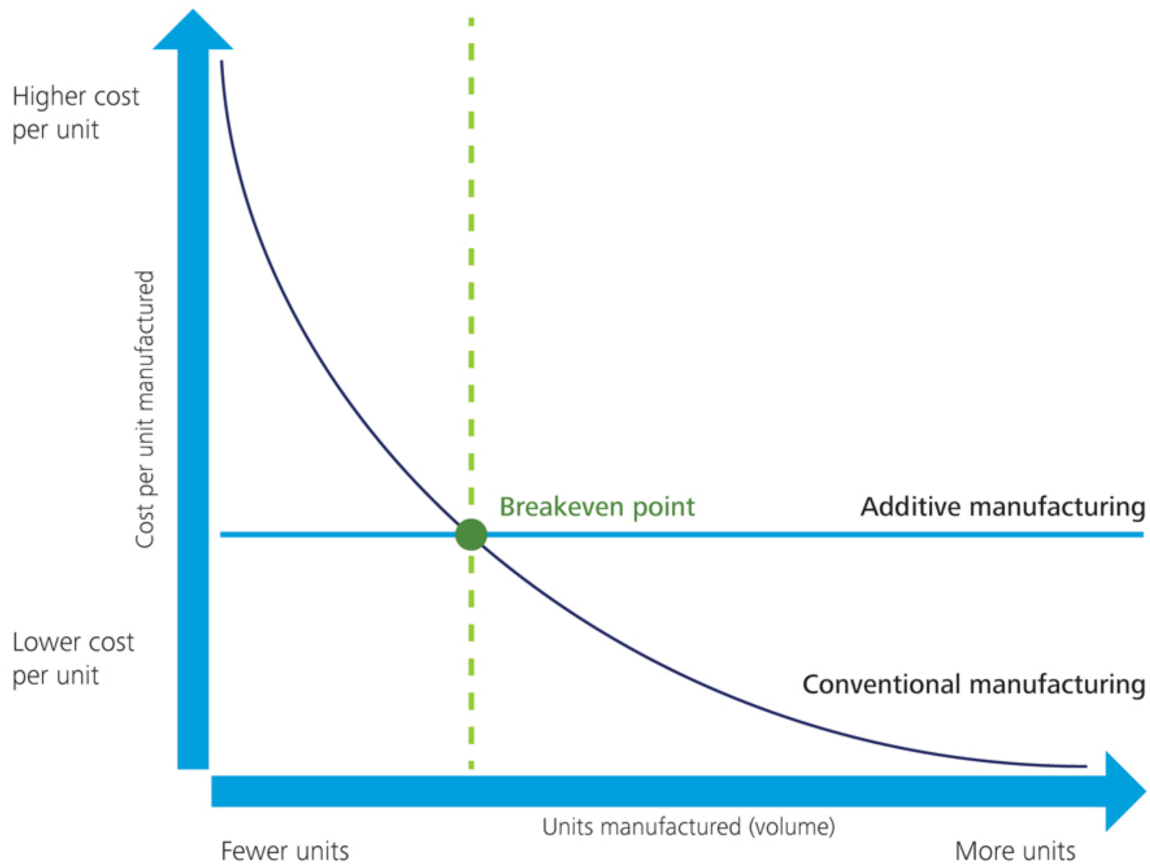
Figure 2. Breakeven analysis comparing conventional and additive manufacturing processes



Source: Mark Cotteleer and Jim Joyce, *3D opportunity: Additive manufacturing paths to performance, innovation, and growth*, Deloitte University Press, http://dupress.com/articles/dr14-3d-opportunity/, accessed March 17, 2015.

Graphic: Deloitte University Press | DUPress.com

Moreover, many AM-produced products cannot be made to the precise tolerances required by regulation, and finishing still requires the use of traditional machining.[11] For example, the Army's RAMBO launcher required both 70 hours of print time and 5 hours of post-print finishing, including tumbling the barrel in an abrasive rock bath to smooth it following printing. Today, there are also a limited number of materials that can be used in AM, and developing process parameters for new materials will take time. Limitations on the materials available for use mean limitations on what can be produced and with what inherent qualities, though these barriers will likely fall with time.

Additive also carries with it unique risks for businesses, many of which center around the effective management of intellectual property and other forms of proprietary knowledge. Because additive is built around the development of a set of instructions that tell a printer precisely how to create a product,

[11] Peter Zelinski, "Will AM Subtract from Machining?," panel discussion, Additive Manufacturing, January 27, 2016, https://www.additivemanufacturing.media/blog/post/video-will-am-subtract-from-machining.

there is less tacit knowledge required in the process of production. This means that knowledge, once it exits a secure environment, can be more readily exploited. Managing this risk will require both integration of technical solutions (e.g., digital rights management) and developing different techniques for supply chain management.

Additive Manufacturing in the Context of Advanced Manufacturing

Additive manufacturing is one part of advanced manufacturing. No authoritative definition exists for what makes manufacturing "advanced," but the U.S. Advanced Manufacturing National Program Office defines advanced manufacturing as the **"**use of innovative technologies to create existing products and the creation of new products. Advanced manufacturing can include production activities that depend on information, automation, computation, software, sensing, and networking."[12]

These "innovative technologies" range from high-performance computing and new information technology to robotics and advanced composite materials. The term can also be applied to manufacturing that takes advantage of innovative business or supply chain management strategies that increase product quality or decrease cost. Whether through technology or technique, the result is greater efficiency and productivity in the manufacturing process.

Where does additive manufacturing fit within this construct? It is an innovative technology, but one that sits at the intersection of various other innovative technologies. It also enables a range of "innovative business of supply chain management strategies." For example, by enabling rapid prototyping on-site, as opposed to production and shipment of prototypes from distant producers, manufacturers can achieve a variety of advantages. These include more rapid design testing and evolution, improved information security, and more consistent quality control in the prototyping stages. Additive manufacturing technologies have also given rise to the "manufacturing as a service" business model, whereby printer manufacturers offer other companies the software and hardware capabilities to print custom models as a service rather than simply selling the equipment.[13]

[12] "Glossary of Advanced Manufacturing Terms," Manufacturing.gov, https://www.manufacturing.gov/news-2/news/glossary-of-advanced-manufacturing-terms/.
[13] PwC, "Five Ways 3-D printing is changing manufacturing."

Seven Key Processes

In 2010, Committee F42 of the American Society for Testing and Materials (ASTM) published a set of classifications that broke AM into seven processes.

1. *Vat Polymerization.*[14] Vat polymerization uses a vat of liquid photopolymer resin, a material that hardens when exposed to light. Ultraviolet light is used to selectively cure the resin, which is supported atop a build platform. Once a layer is cured, the build platform then lowers beneath the surface and the process repeats, with layers building on preceding layers until the full structure is formed.
2. *Material Jetting.* A print head jets material, either wax or a polymer, onto a build platform, where it is allowed to cool or hardened by UV light. Successive layers are then built on top of the first, forming the desired three-dimensional shape.
3. *Binder Jetting.* Binder jetting involves the use of a powder base material and a binding agent. Inside the build chamber, a layer of powder is first laid down. A print head then selectively applies binding agent in accordance with the design specifications. The build platform moves downward, another layer of powder is deposited, and the process repeats, alternating powder and binding agent.
4. *Material Extrusion.* Material extrusion is the most popular method of three-dimensional printing worldwide. The build material is heated and drawn through a nozzle, which extrudes it to create the first layer. The build platform then lowers and the process is repeated to create the finished object.
5. *Powder Bed Fusion (sintering and melting).* Powder Bed Fusion (PBF) is the process of using either a laser or electron beam to selectively melt and fuse powder together. The powder material can be a range of polymers and metals, including nylon, steel, aluminum, and titanium. In PBF, a first layer of powder is deposited and a laser or electron beam heats the powder in accordance with the design specifications. A platform then lowers the model, and another layer of powder is applied using a roller or blade. The process repeats until the full model is formed.
6. *Sheet Lamination.* Sheet lamination is a process whereby sheets of material are bonded together and each layer, after the sheet is added and bonded, are cut to the appropriate shape using either a laser or a knife. Any sheet material that can be rolled may be used in sheet lamination, including paper, plastic, and some sheet metals.
7. *Directed Energy Deposition.* Directed energy deposition (DED) involves the use of a laser or electron beam to melt a powder or wire, which is then deposited onto a specified surface, where it solidifies. DED offers high accuracy and excellent control over grain structure, which makes it useful for high-quality repairs and fabrication of 3D parts.

[14] For additional information and video demonstrations of these processes, a thorough explanation is available from Loughborough University's Additive Manufacturing Research Group at http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/. For abbreviated descriptions of each of the seven processes, see page 17 of Thomas and Gilbert, "Costs and Cost Effectiveness of Additive Manufacturing: A Literature Review and Discussion."

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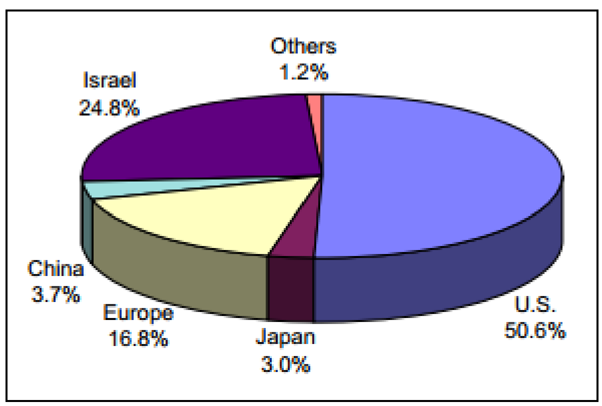
Characteristics of Additive Manufacturing Development

"Additive manufacturing" can be a misleading term. While this paper has focused on expensive, massive machines printing parts for jet engines, the term can equally be applied to the creation of a fidget spinner by a high school student on a printer purchased for less than $200. This is because of a split in the technology path nearly 20 years ago, with one path focused on flexible prototyping and another on the production of high-value, highly engineered components.

To understand how the technology arrived at its current state, a brief historical overview may be helpful. The modern development of additive dates roughly to the early 1980s, with the development of, first, stereolithography techniques and, subsequently, selective laser sintering (the foundation of PBF) in 1986. Other advances, such as the development of fused deposition modeling, came in the early 1990s, and research for the remainder of the decade largely focused on prototyping applications of the technology. By the early 2000s, the continued advance of additive technologies led to their adoption in the automotive, aerospace, and medical sectors. Around this time there also came a split in the technology path, with one path focused on developing capabilities for flexible prototyping and another focused on the production of high-value industrial parts. In 2009, the American Society for Testing and Materials International established a committee on Additive Manufacturing Technologies to help standardize aspects of the industry, publishing standard terminology for AM two years later.

From a market perspective, AM has grown rapidly and consistently since its emergence in the late 1980s, albeit from a very low base. In their 2017 annual report, Wohlers Associates estimates that the compound annual growth rate of the AM industry from 1988–2016 was around 25 percent. In 2016, the total size of the market reached $6.06 billion, with worldwide revenues growing 17.4 percent over the previous year.[15] However, even having grown at double-digit rates for over a quarter century, the AM industry still accounts for less than one-tenth of 1 percent of the global manufacturing sector. Estimates produced by NIST in 2014 suggest that the industry will not reach $100 billion in annual shipments until around 2030. This suggests that while AM may prove disruptive for specific industry subsectors where adoption rates are high, its impact on the overall structure of global manufacturing will likely be felt more gradually, barring any significant discontinuities in current trends.



Source: Wohlers Associates, Inc.

[15] Wohlers Associates, "*Wohlers Report 2017* Shows Vibrant New Business Activity in 3D Printing with Softened Growth Worldwide," April 3, 2017, https://wohlersassociates.com/press72.html.

According to Wohlers and a study by the National Defense University, the United States accounts for just over half of all global sales in AM systems between 1988 and 2014, followed by Israel and Europe.[16]

Today, a variety of advances are underway that are improving the viability of AM processes as a business proposition. On the hardware front, these include improvements in the range of materials that can be used in AM systems, in the ability to monitor and control AM processes to ensure consistent quality,[17] in the size of structures that can be created using AM techniques,[18] [19] in the speed with which products can be printed,[20] in the range of environments in which printers can operate,[21] and in the ability to ensure the integrity of printed products.[22] [23] On the software end, efforts are underway to improve the ease of designing components, allow for more thorough modeling and testing of designs prior to printing, and improve the efficiency with which printers operate,[24] among other advancements. These advances, alongside widening industry awareness of the utility and potential applications of AM, are also leading to the development of new business models (such as manufacturing as a service) and efforts to simplify supply chains, improve inventory management, and streamline product delivery using AM techniques.

Challenges

Like any developing technology, additive-manufacturing techniques will face a variety of challenges. These include technical challenges, such as ensuring product consistency, quality, and integrity, an issue that some have characterized as the single most important barrier to widespread adoption of AM techniques.[25] Establishing industry and regulatory standards to promote adoption and ensure safety and reliability represents another basket of challenges. In the absence of uniform standards, it can be difficult for businesses to weigh the costs and benefits of attempting to integrate AM techniques into

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[16] Eisenhower School for National Security and Resource Strategy, National Defense University, "Industry Report: Advanced Manufacturing," Spring 2017 Industry Study, https://ammo.ncms.org/wp-content/uploads/ADMAN-Group-Paper.pdf.

[17] Ian Wright, "5 Key Advanced for Metal Additive Manufacturing," Engineering.com, February 22, 2016, https://www.engineering.com/3DPrinting/3DPrintingArticles/ArticleID/11537/5-Key-Advances-for-Metal-Additive-Manufacturing.aspx.

[18] Tomas Kellner, "GE Is Building the World's Largest 'Additive' Machine for 3D Printing Metals," *GE Reports,* June 20, 2017, https://www.ge.com/reports/ge-building-worlds-largest-additive-machine-3d-printing-metals/.

[19] Steven J. Keating, Julian C. Leland, Levi Cai, and Neri Oxman, "Toward site-specific and self-sufficient fabrication on architectural scales," *Science Robotics* 2, issue 5 (April 26, 2017), http://robotics.sciencemag.org/content/2/5/eaam8986.

[20] Sandra Zisti, "3D Printing: Facts & Forecasts," *Pictures of the Future*, Siemens, October 1, 2014, https://www.siemens.com/innovation/en/home/pictures-of-the-future/industry-and-automation/Additive-manufacturing-facts-and-forecasts.html.

[21] NASA, "The Geometry of Success: Archinaut Project Conducts First Large-Scale Additive Manufacturing Build in Space-like Environment," August 10, 2017, https://www.nasa.gov/mission_pages/tdm/irma/the-geometry-of-success-archinaut-project-conducts-first-large-scale-additive-manufacturing.html.

[22] John Toon, "Print No Evil: Three-Layer Technique Helps Secure Additive Manufacturing," Georgia Tech News Center, August 16, 2017, http://www.news.gatech.edu/2017/08/16/print-no-evil-three-layer-technique-helps-secure-additive-manufacturing.

[23] Erhard Brandl, Christoph Leyens, and Frank Palm, "Mechanical Properties of Additive Manufactured Ti-6Al-4V Using Wire and Powder Based Processes," *IOPScience* (2011 IOP Conference Series: *Materials Science and Engineering* 26), http://iopscience.iop.org/article/10.1088/1757-899X/26/1/012004/meta.

[24] Samuel Lensgraf, "Beyond layers: A 3D-aware toolpath algorithm for fused filament fabrication," *IEEE International Conference on Robotics and Automation*, May 16, 2016, https://ieeexplore.ieee.org/document/7487546/.

[25] U.S. Government Accountability Office, "3D Printing: Opportunities, Challenges, and Policy Implications of Additive Manufacturing: Highlights of a Forum," June 2015, http://www.gao.gov/assets/680/670960.pdf.

established supply chains. On the regulatory side, so far there have been no major disasters where AM has been implicated; however, there is a risk that such an event could generate political pressure to act in manner that may not be conducive to the technology's development and more widespread adoption. A third and related set of challenges involves education. This is particularly difficult given both the sophistication of AM technology and the range of stakeholders involved, from business managers who may be considering integration of AM technologies, to the designers, engineers, and technicians involved in applying them, to the public and elected officials who ultimately determine how these emerging processes are regulated. This last is especially challenging given the hyperbole that often accompanies discussions of AM, which can obscure the reality of incremental changes in a complex global manufacturing environment.

Technology Challenges

Companies are concerned with making sure they have a reliable and certified supply base. However, one salient feature of additive manufacturing is the number of small companies. A natural concern, then, is the shape of the regulatory environment, a challenge that industry has begun to engage in a variety of ways.

For example, General Electric has made a considerable effort in additive manufacturing technology, already operating 10 additive manufacturing centers in the United States. GE's approach to product consistency is not so different from other forms of manufacturing: it controls the material supply, has developed specifications for all of the components used, and carefully controls the machining processes. This allows them to create highly controlled parts with the same properties as traditional manufacturing, while leveraging the advantages of AM techniques and gaining the experience and know-how to further develop their use.

More generally, control and monitor of inputs tends to yield consistent output. This is a simple principle, but can be difficult and costly to apply in practice, particularly given the complexity of the AM process and the newness of the field. For example, variables to be controlled in order to ensure consistent build quality can include laser power, laser scan speed, and build chamber temperature, among others.[26] In fact, the Federal Aviation Administration recognizes over 100 process parameters that can bear on the quality and characteristics of the final product.[27]

To help with this issue, the American Society for Testing and Materials established Committee F42 on Additive Manufacturing Technologies, which has in turn established a subcommittee on testing, working with industry stakeholders to produce standards such as the "Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes." Efforts like this appropriately focus on understanding and evaluating the characteristics of products produced via AM,

[26] Ian Wing, Rob Gorham, and Brenna Sniderman, "3D opportunity for quality assurance and parts qualification," *Deloitte Insights*, November 18, 2015, https://dupress.deloitte.com/dup-us-en/focus/3d-opportunity/3d-printing-quality-assurance-in-manufacturing.html.
[27] Jim Kabbara and Michael Gorelik, "FAA Perspectives on Additive Manufacturing," Federal Aviation Administration, March 9, 2016, http://www.nianet.org/ODM/ODM%20Wednesday%20presentations%20Final/7%20Kabbara%20On-Demand%20Workshop%20AM%20Presentation(03-09-2016.pdf.

allowing companies to focus on ensuring that their products can meet the thresholds demanded by their end-uses.

In an ideal world, standards have the potential to promote industrial and market efficiency, foster international trade, lower barriers to market entry, diffuse new technologies, and protect human health and the environment.[28] At a more micro level, standards can help specify requirements, communicate guidance, document best practices, define test methods and protocols, document technical data, and accelerate new technology adoption.[29] When standards are successful in these regards, they promote growth and foster trust, generating a positive feedback cycle that improves and safeguards both aggregate and individual welfare.

However, standards can also have the opposite effect, creating unnecessary barriers to entry, stifling innovation, impeding trade between different legal jurisdictions, and generating other ill effects. This is particularly true when standards are developed in isolation from industry input, neglecting the greater firsthand experience that producers typically have in assessing the viability and outcomes from their own internal processes. Another issue is when states seek to use standards to deliberately discriminate against foreign producers or otherwise use standards as a tool for advancing a political or security agenda, which can undermine trust, efficiency, and, in many cases, quality.[30]

In general, the U.S. approach to standards in AM and more generally has focused on evaluating the properties of the final product. The focus is on developing adequate testing standards to ensure that a final product exhibits the characteristics necessary to safely perform its intended function. By contrast, the European Union tends to have a more prescriptive approach, which includes more process-based standards. Although the United States remains the single-largest market for AM by revenues,[31] expert interviews suggest that some EU countries, such as Germany, are making leading contributions in standard setting.

This suggests both risks and opportunities. One key risk is that overly prescriptive standards developed in Europe will become barriers to entry for U.S. companies, accustomed to a different regulatory ecosystem and process, and could proliferate in other parts of the world, such as Asia. This would simultaneously expand the market for European companies, while potentially restricting the market of U.S.-based producers, diverting talent, capital, and research activities outside the United States. At the same time, the fact that standard-setting remains in an early stage suggests opportunities to promote cooperation, harmonizing standards where possible and potentially establishing equivalency in other areas to avoid market fragmentation.

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[28] Raymond G. Kammer, "The Role of Standards in Today's Society and in the Future," speech to the House Committee on Science Subcommittee on Technology, September 13, 2000, https://www.nist.gov/speech-testimony/role-standards-todays-society-and-future.
[29] Shawn Moylan, "NIST Perspective on Additive Manufacturing Standards," National Institute of Standards and Technology, http://ws680.nist.gov/publication/get_pdf.cfm?pub_id=919658.
[30] Adam Segal, "China, Encryption Policy, and International Influence," Hoover Institution Series Paper No. 1610, November 28, 2016, https://www.hoover.org/sites/default/files/research/docs/segal_webreadypdf_updatedfinal.pdf.
[31] Eisenhower School for National Security and Resource Strategy.

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One positive step in this regard is the October 2016 announcement of a partnership between the International Organization for Standardization (ISO) and ASTM International on the Additive Manufacturing Standards Development Structure.[32] [33] The ASTM is a multi-stakeholder organization, involving users, producers, consumers, and other interested parties in the process of developing voluntary standard. Its cooperation with the ISO provides an opportunity to help globalize standards developed in the United States with industry input, as well as establish a common understanding of priority areas for standard development.

A similarly positive development has been the joint work of America Makes and the American National Standards Institute (the official U.S. representative at the ISO) on the Additive Manufacturing Standardization Collaborative (AMSC), which released a standardization roadmap in February 2017.[34] The AMSC roadmap identifies "standards and standards in development, assess gaps, and make recommendations for areas where there is a perceived need for additional standardization and/or pre-standardization research and development."[35]

There are also opportunities to leverage the leading position of sector-specific U.S. regulators in promoting international cooperation and the diffusion of voluntary, industry-led standards. For example, the U.S. Federal Aviation Authority (FAA) is widely viewed by its foreign counterparts as a leading authority in this issue, meaning that FAA certification can go a long way toward opening other markets to U.S. producers.

Education and Workforce Development

Growth in the AM industry has led to a corresponding growth in related job opportunities. Estimates by Wanted Analytics show that the number of job ads requiring workers with 3D printing skills increased nearly 2,000 percent from 2010 to 2014.[36] However, the Society of Manufacturing Engineers estimated in 2011 that 9 out of 10 manufacturers were having trouble finding qualified candidates for these jobs, particularly small and medium-sized enterprises. More recently, a 2015 study by Deloitte and The Manufacturing Institute estimated that the next decade would see 3.5 million manufacturing jobs that

[32] Bridget Butler Millsaps, "Furthering 3D Printing Worldwide: ISO & ASTM International Create Additive Manufacturing Standards Development Structure," 3DPrint.com, October 6, 2016, https://3dprint.com/151726/3d-printing-iso-astm-standards/.
[33] ASTM, "Additive Manufacturing Standards Structure," https://www.astm.org/COMMIT/F42_ISOASTM_AdditiveManuStandardsStructure.pdf.
[34] American National Standards Institute (ANSI), "America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC)," https://www.ansi.org/standards_activities/standards_boards_panels/amsc/Default?menuid=3.
[35] ANSI and America Makes, "Standardization Roadmap for Additive Manufacturing: Version 1.0," February 2017, https://share.ansi.org/Shared%20Documents/Standards%20Activities/AMSC/AMSC_Roadmap_February_2017.pdf.
[36] Louis Columbus, "Demand for 3D Printing Skills Is Accelerating Globally," *Forbes*, September 15, 2014, https://www.forbes.com/sites/louiscolumbus/2014/09/15/demand-for-3d-printing-skills-is-accelerating-globally/#f40db594cf7e674153264cf7.

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needed to be filled, of which 2 million would go unfilled due to a lack of qualified candidates (among other issues).[37] [38]

Importantly, this is only one aspect of the education gap that must be addressed in order to realize the full potential of AM processes. Education is also needed for regulators, program officers, chief engineers, and others involved in shaping the ecosystem for AM and integrating it alongside or as a substitute for existing processes.[39] In other words, there is both the challenge of training the next generation of engineers and designers who will enter the workforce over the decade ahead, and retraining those already active in the workforce to take advantage of emerging technologies and business models. Although market forces will do some of the work in this regard, it is likely that some form of local, state, and federal government involvement—in cooperation with stakeholders such as industry and academia—will be necessary to ensure the United States remains the global leader in the development and application of AM technologies.

Security

It is a virtual certainty that malicious actors will seek to take advantage of AM technologies to do harm, or will seek to undermine the integrity of AM systems. In fact, these actors, whether lone wolves, organized crime, or foreign governments, are likely to not only be users of these technologies, but innovators in their own right. However, overly aggressive efforts to restrict access to AM technologies will not only harm growth and the rate at which these technologies are integrated, but are unlikely to succeed in promoting security.

A variety of factors suggest that solely attempting to prevent these actors from acquiring AM hardware or materials is not a viable approach.[40] These include the increasing ubiquity of 3D printers and the dual-use nature of key inputs. Although progress has been made to adopt controls on certain AM equipment and software through the Wassenaar Arrangement on Export Controls, additional attention to managing the software and data side will be necessary. This will need to include considering how to maintain up-to-date threat intelligence, limit access to certain programs, blueprints, and other data, and more generally monitor the flow of relevant data.

Another issue will be securing AM processes from various types of cyberattack, which might involve the theft of design files, printing of unauthorized objects, damage to AM hardware, printing of dangerous or illegal objects, or changes in design files to deliberately introduce flaws. For example, in a 2016 paper, a

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[37] Deloitte and Manufacturing Institute, *The skills gap in U.S. manufacturing: 2015 and beyond*, February 2015, http://www.themanufacturinginstitute.org/~/media/827DBC76533942679A15EF7067A704CD.ashx.
[38] Eric Vazquez, Michael Passaretti, and Paul Valenzuela, "3D opportunity for the talent gap," *Deloitte Insights*, March 24, 2016, https://dupress.deloitte.com/dup-us-en/focus/3d-opportunity/3d-printing-talent-gap-workforce-development.html#endnote-sup-15.
[39] The New Growth Group, *Additive Manufacturing: State of the Workforce and Industry in Northeast Ohio*, October 16, 2016, https://www.tri-c.edu/programs/engineering-technology/manufacturing-engineering/3d-digital-design-and-manufacturing-technology/documents/additive-manufacturing-state-of-the-workforce-and-industry-in-northeast-ohio.pdf.
[40] Michael Stehn, Ian Wing, Tina Carlile, Joe Dichairo, and Joe Mariani, "3D opportunity for adversaries," *Deloitte Insights*, August 22, 2017, https://dupress.deloitte.com/dup-us-en/focus/3d-opportunity/national-security-implications-of-additive-manufacturing.html.

group of researchers was able to alter the blueprints for a 3D-printed propeller in a manner undetectable through visual inspection. The result was that the propeller broke apart soon after takeoff, crashing and destroying the drone to which it was attached.[41] Considering that early adopters of AM technologies have included the healthcare and aerospace sectors, securing against cyberattacks represents an important priority for ensuring the viability of AM integration.

There are a variety of means for mitigating these risks, from encryption of design files to the introduction of unique chemical identifiers into AM products. As with many cybersecurity challenges, however, the issue of promoting adoption of best practices will be at least as critical as developing appropriate technical solutions (if not more so). In this regard, promoting cooperation between public- and private-sector security practitioners and ensuring that the development of best practices remains a collaborative, iterative process will be essential.

The Near-term Technology Outlook

Although AM is often discussed in the context of a "revolution" in manufacturing, highlighting the disruptive potential of an idealized form of the technologies, the reality is that progress over the next five years is more likely to be linear. Even if, as most industry experts expect, double-digit compound annual growth rates continue over the near term, the total value of AM production is not expected to reach $100 billion until roughly 2030. For comparison, 2016 sales revenue from Germany's top three automotive original equipment manufacturer (OEM) parts suppliers exceeded $100 billion.[42]

Significant progress in both AM adoption rates and the underlying technologies is expected to continue over the near term. On the adoption front, advances are likely to be fastest in subsectors of those broader sectors where initial attempts at integrating AM processes have already proven successful, namely the medical/dental, aerospace, motor vehicle, industrial/business machines, consumer electronics, and military sectors. For example, the *Harvard Business Review* cites the U.S. hearing aid industry as one where a complete switch from traditional to additive manufacturing took place in less than 500 days[43]—and yet AM still accounted for only 0.04 percent of value-added in the medical sector in 2011.

On the technologies front, as discussed above, advances are likely in the range of materials available, the speed of printing, the environments in which printing can take place, and other areas, which will be a product of hardware, software, and material science improvements. The overall ecosystem will also improve, as more raw materials suppliers enter the market and gain experience and as available printing capacity increases. However, at least over the near term, traditional subtractive manufacturing will remain the mode of choice for large batch productions (largely for cost reasons), simple parts, stampings, and simple turn machine components, and large objects (largely for engineering reasons).

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[41] iTrust Centre for Research in Cyber Security, "Dangerous and Costly New Cyber Threat: Hacking 3D Manufacturing Systems Demonstrated," September 2016, https://itrust.sutd.edu.sg/research/projects/security-additive-manufacturing/.
[42] Crain Communications, "Automotive News: Top Suppliers," *Automotive News*, June 26, 2017, http://www.autonews.com/assets/PDF/CA110870620.PDF.
[43] Richard D'Aveni, "The 3-D Printing Revolution," *Harvard Business Review*, May 2015, https://hbr.org/2015/05/the-3-d-printing-revolution.

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Prototyping and parts with complex geometries are likely where AM will continue to stand out most over this timeframe.

Since AM remains at a relatively early stage in its development and deployment, a high-profile failure of an AM-produced part would represent a significant threat to the industry's development. Those sectors furthest advanced in integrating AM processes, such as the medical and aerospace sectors, generally require parts built with an extreme degree of precision and requiring precise tolerances. There is an obvious reason for this: the success or failure of these parts can be the difference between life or death for patients and passengers. However, the more time passes, the more AM processes are widely adopted, and the more evidence of the ability of AM-produced parts to function safely accumulates, the less vulnerable the industry will be to any single incident.

The Role of Government

The U.S. economy continues to lead the world in the development and implementation of advanced technology with what is, in essence, a *laissez-faire* approach. Public-private consortia like America Makes have played a useful convening role for education and standards development, but the U.S. government and the private sector are primarily focused on complementary but separate roles. R&D investment by the U.S. government principally takes place at academic institutions and government entities like national laboratories (e.g., Lawrence Livermore) and Federally Funded Research and Development Centers. Beyond basic research, the vast majority of R&D investments are private, directed at commercialization and application refinement. U.S. regulatory agencies are in a position to accelerate technical process by increasing rates of adoption and extension of additive manufacturing innovations, so long as regulation is not unintentionally stifling. To date, their track record has been good, and many agencies have experts focused on integrating additive manufacturing into existing regulation.

Germany is a useful comparison economy. German industrial specialization has many similarities to the United States, and unsurprisingly many of Europe's additive suppliers are German companies. However, the German government's approach to R&D spending differs considerably from the U.S. model. In the broader context of advanced manufacturing, Germany operates the Fraunhofer Institute, consisting of 69 different entities with a staff of 24,500 and annual research budget of 2.3 billion euros. It began as a government-sponsored entity but is now a virtually independent research entity, with 75 percent of funding from sources other than the German government. While the Fraunhofer model deserves attention, it is not a demonstrably superior approach to the private commercial R&D approach of leading U.S. advanced manufacturing firms.

Conclusion

Additive manufacturing has "arrived" as a suite of innovations that will help reshape how things are made. Today's additive manufacturing reality lies somewhere between the enthusiasts who see a revolution in production and the skeptics who point to limited applications due to size and material constraints. The technologies, processes, and end-market applications for additive manufacturing are

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likely to improve and expand in the coming years, and policymakers should support continued basic research and expert regulation to support expansion and improvement.

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