United States Government Accountability Office
Report to Congressional Requesters

June 2015

3D PRINTING

Opportunities, Challenges, and Policy Implications of Additive Manufacturing

Accessible Version

GAO-15-505SP

GAO Highlights Summary Page

3D Printing

Opportunities, Challenges, and Policy Implications of Additive Manufacturing

highlights of a forum

Convened by the Comptroller General of the United States

June 2015

View **GAO-15-505SP**. For more information, contact Timothy Persons, Chief Scientist, at (202) 512-6412 or **personst@gao.gov**

Why GAO Convened This Forum

Additive manufacturing has the potential to fundamentally change the production and distribution of goods. Unlike conventional or subtractive manufacturing processes, such as drilling, which create a part by cutting away material, additive manufacturing builds a part using a layer-by-layer process. Additive manufacturing has been used as a design and prototyping tool, but the focus of additive manufacturing is now shifting to the direct production of functional parts— parts that accomplish one or more functions, such as medical implants or aircraft engine parts—that are ready for distribution and sale.

On October 15-16, 2014, GAO, with the assistance of the National Academies, convened a forum to discuss the use of additive manufacturing to directly produce functional parts, including its (1) opportunities, (2) key challenges, and (3) key considerations for any policy actions that could affect its future use.

Forum participants included officials from government, business, academia, and nongovernmental organizations that were selected to represent a range of viewpoints and backgrounds. This report summarizes the ideas and themes that emerged during the forum and the collective discussions of the forum participants. This report does not necessarily represent the views of the organizations whose representatives participated in the forum, including GAO. Participants were given the opportunity to comment on a draft of this report and their technical comments were incorporated, as appropriate.

What Participants Said

Forum participants identified many opportunities for using additive manufacturing— also known as three-dimensional (3D) printing—to produce functional parts and discussed benefits that have been realized in the medical, aerospace, and defense sectors. For example, they said that the medical industry is using additive manufacturing to produce customized prosthetics and implants, including cranial implants (see fig.). Because it is made specifically for a patient, the part results in a better fit, which leads to a better medical outcome. In the aerospace industry, participants said additive manufacturing was used to design and produce a complex jet engine fuel nozzle as a single part, which will reduce assembly time and costs for the engine (see fig.). Participants identified some future applications of additive manufacturing including enhancing supply chain management. Overall, participants concluded that additive manufacturing will not replace conventional manufacturing, but rather it will be an additional tool for manufacturers to use when it is appropriate from a cost-benefit perspective.

Forum participants identified three broad groups of challenges in using additive manufacturing to produce functional parts: (1) ensuring product quality,

(2) limited design tools and workforce skills, and (3) supporting increased production of functional parts. First, they identified challenges related to building quality parts, such as the need to improve the quality control of the additive manufacturing process. Second, they said that existing design and analytical tools combined with an insufficiently skilled workforce could limit the use of additive manufacturing and its ability to reach its potential for greater innovation. Finally, participants identified challenges that affect the increased production of functional parts, such as the need for an improved industrial infrastructure, including more robust supply chains of machines and materials.

Forum participants identified key considerations for potential federal policy actions that could affect the future use of additive manufacturing, including industry challenges, areas affected by additive manufacturing growth, and trade-offs.

Although there was no consensus on specific policy actions needed and many participants suggested caution on potential government action, participants discussed several areas of potential government involvement, such as coordinating standards setting, considering risks for infringement of intellectual property rights with regard to additive manufacturing products, and encouraging a national dialogue about the government’s role and its goals.

Contents

GAO Highlights Summary Page		i
	3DPrinting	i
	Opportunities, Challenges, and Policy Implications of Additive Manufacturing	i
Letter		1
	Foreword	3
	Introduction	5
	Opportunities Exist to Use Additive Manufacturing for the Production of Functional Parts and for Other Applications	15
	Industry Faces Key Challenges in Using Additive Manufacturing to Produce Functional Parts	25
	Key Considerations for Federal Policy Actions That Could Affect the Future Use of Additive Manufacturing for Production of Functional Parts	38
Appendix I: Objectives, Scope, and Methodology		46
Appendix II: Forum Participants		52
Appendix III: Forum Agenda		56
Appendix IV: Challenges Identified by Forum Participants		58
Appendix V: GAO Contact and Staff Acknowledgments		61
Table		
	Table 1: Types of Additive Manufacturing Processes	8
Figures		
	Figure 1: Conceptual Comparison of Subtractive and Additive Manufacturing	6
	Figure 2: Examples of Additive Manufacturing Systems	11
	Figure 3: Desktop 3D Printer	12

Figure 4: Additively Manufacturing a Satellite Propellant Tank Using Electron Beam Technology 17
Figure 5: Additive Manufacturing Systems in Expeditionary Labs 18
Figure 6: Jet Engine Fuel Nozzle 19
Figure 7: Complex Internal Structure of a Knee Implant 20
Figure 8: Custom Patient-specific Cranial Implant 21
Figure 9: Simple Additively Manufactured Replacement Parts 24
Figure 10: Examples of Variability in Additive Manufacturing Materials, Machines, Manufacturing Practices, and Final Parts 27
Figure 11: Examples of Additively Manufactured Products with More Complex Shapes (Aerospace Duct (left) and Trussed Air Foils (right)) 32

441 G St. N.W.
Washington, DC 20548

June 24, 2015

The Honorable Lamar Smith
Chairman
Committee on Science, Space, and Technology
House of Representatives

Dear Mr. Chairman:

Additive manufacturing—also known as three-dimensional (3D) printing—has the potential to fundamentally change the structure and management of supply chains and the production and distribution of goods. As the technology has matured, the use of additive manufacturing has become more widespread. Additive manufacturing has been used as a design and prototyping tool since its inception, but the focus of additive manufacturing is now shifting to the production of functional parts and products, such as jet engine parts and hearing aids.

On October 15-16, 2014, GAO, with the assistance of the National Academies, convened a select group of leaders and experts for a forum to discuss key issues related to using additive manufacturing for production of functional parts. These participants included representatives of government, business, academia, and nongovernmental organizations and were selected to represent a range of viewpoints and backgrounds. The forum offered a series of facilitated discussions designed to address the following questions:

1. What are the opportunities to produce functional parts using additive manufacturing?
2. What are the key challenges, if any, to using additive manufacturing to produce functional parts?
3. What are the key considerations for any policy actions that could affect the future use of additive manufacturing to produce functional parts?

This report summarizes the ideas and themes that emerged during the forum and the collective discussions of the forum participants. The report does not necessarily represent the views of the organizations whose representatives participated in the forum, including GAO. Participants were given the opportunity to comment on a draft of this summary report. Appendix I provides more details on the scope and methodology to plan and conduct the forum and to prepare this report. Appendix II provides a list of the forum participants, and appendix III provides the forum agenda. Appendix IV provides a summary of the participant-identified challenges to using additive manufacturing to produce functional parts.

We conducted our work from March 2014 to June 2015 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to our objectives. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations in our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

This report is available at no charge on the GAO website at http://www.gao.gov. If you or your staff have any questions about this report, please contact Timothy M. Persons, Chief Scientist, at (202) 512-6412 or personst@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff that made key contributions to this report are listed in appendix V.

I would like to thank the forum participants for taking the time to share their knowledge, insights, and perspectives on this important and strategic national topic.

Sincerely yours,

Gene L. Dodaro
Comptroller General
of the United States

Foreword

Additive manufacturing has existed for decades, but is now receiving increased attention because of its potential to transform the manufacturing industry and how goods are produced, distributed, and sold to consumers. For instance, additive manufacturing could make existing product supply chains more efficient by allowing for more on demand production, which could reduce the need to maintain large product inventories and spare parts, and allow for the localized production of goods closer to consumers. The do-it-yourself or maker movement has already benefited from the increasing availability of low-cost 3D printers and uses additive manufacturing technology to create a wide variety of items, including jewelry, toys, sculptures, and other artistic products. Additive manufacturing holds the potential for disrupting existing and creating new markets, but the technology is in its relative infancy and it may be years or decades before it reaches levels of confidence comparable to what the industry has with the more familiar conventional manufacturing processes and materials.

We focused this forum on the opportunities, challenges, and policy implications of the use of additive manufacturing for functional part production. As opposed to artistic products that may only be aesthetically pleasing, functional parts have structural and performance requirements to accomplish the function it needs to perform. Such parts, which could include items as simple as knobs or as complex as automobile or jet engine parts, need to be reliably and consistently produced even as the context for safety and performance can vary widely. As a result, there could be significant problems with poorly manufactured functional parts, particularly those used for safety-critical applications, such as parts for aircraft or medical products. Nevertheless, the potential benefits of using additive manufacturing for part design and production include the ability to fabricate more complex shapes, reduced manufacturing cycle times, costs, and supply chain risks, and more efficient use of manufacturing materials, which could potentially reduce waste in the manufacturing process and its resulting environmental effects.

However, the role of government policy making for additive manufacturing needs to be better understood. Determining that role will require a better understanding of the opportunities afforded by additive manufacturing for functional part production and the challenges currently faced. Further, as the use of additive manufacturing increases, particularly for safety-critical parts and products, it will be important to understand any potential concerns it raises.

I am grateful to all the forum participants for their time and insights during the meeting and throughout the development of this report.

Sincerely yours,

T.M. Persons

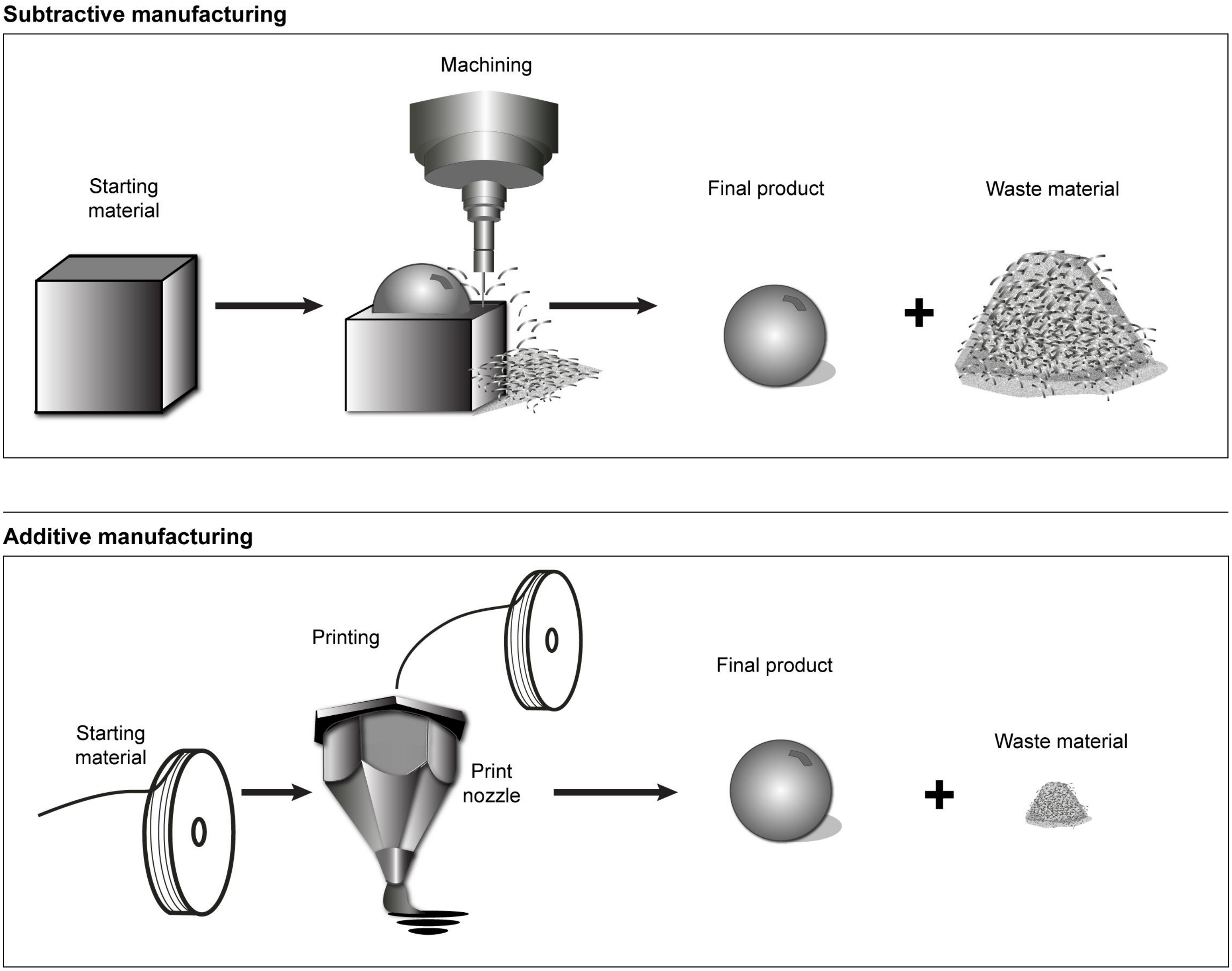
Timothy M. Persons, Ph.D.
Chief Scientist
Director, Center for Science, Technology, and Engineering

Introduction

Additive manufacturing is a layer-by-layer process of producing 3D objects directly from a digital model.[1] As seen in figure 1, unlike conventional or subtractive manufacturing processes, such as drilling or milling, which create a part or product by cutting away material from a larger piece, additive manufacturing builds a finished piece in successive layers, generally without the use of molds, casts, or patterns, which can potentially lead to less waste material in the manufacturing process.

[1]Additive manufacturing and 3D printing are terms that are often used interchangeably, as is the case in this report.

Figure 1: Conceptual Comparison of Subtractive and Additive Manufacturing



Sources: GAO (analysis); Art Explosion (images). | GAO-15-505SP

While the concepts have existed for decades, commercialization of additive manufacturing began in the mid-1980s and its first uses were primarily for presentation purposes. For more than 20 years, the technology has been evolving as a design and prototyping tool. Additive manufacturing offers the ability to rapidly create prototypes that can help validate the fit, form, and functionality of proposed products, which has provided both great time and cost savings in the product development cycle. As the technology has matured, the use of additive manufacturing has become more widespread and has expanded into more applications. For instance, one of the significant applications for additive manufacturing has been the production of tools and casts for conventional manufacturing. Lower manufacturing tool costs have allowed manufacturers to produce in lower volumes that previously may not have been cost-beneficial.

The use of additive manufacturing for prototyping and manufacturing tooling has helped to improve the efficiencies of conventional manufacturing processes, and the use of additive manufacturing is now shifting to the direct production of goods that are ready for distribution and sale. The emergence of desktop equipment for additive manufacturing has enabled the production of jewelry, art replicas, toys, models, and other artistic products. However, it is the potential to use additive manufacturing to produce functional parts and products, particularly in critical applications such as medicine and aerospace, that has generated a lot of attention. For instance, additive manufacturing has been described as having the potential to transform the manufacturing industry and lead to a "new industrial revolution," a term used by The Economist in 2011.[2] In 2012, the National Defense University said that additive manufacturing was a prospective game-changer that could be part of a U.S. manufacturing revolution.[3] In July 2014, Gartner, a leading information technology research firm, identified consumer and industrial applications of 3D printing, among others, as having transformational business benefits, but estimated that mainstream adoption would not occur for 5 to 10 years.[4]

The manufacturing industry's adoption of additive manufacturing to directly produce goods is in its infancy but growing rapidly. In 2011, the National Institute of Standards and Technology (NIST) estimated that the United States produced an estimated $246.1 million from additively manufactured goods, which represented about one-hundredth of 1

[2]"3D Printing: The Printed World," *The Economist* (Feb. 10, 2011).

[3]National Defense University, "Toward the Printed World: Additive Manufacturing and Implications for National Security," *Defense Horizons* (September 2012).

[4]Gartner, *Hype Cycle for 3D Printing, 2014* (July 21, 2014).

percent of all manufactured goods produced in the United States.[5] In the 2-year period from 2011 to 2013, Wohlers Associates, an independent consulting firm that specializes in additive manufacturing, estimated that the global revenue from additively manufactured goods grew more than 65 percent from $642.6 million in 2011 to $1.065 billion in 2013.

Several Types of Additive Manufacturing Processes and Technologies Exist

Additive manufacturing is not a single type of technology or process. All additive manufacturing systems employ a general layer-by-layer approach, but they use a wide variety of technologies, materials, and processes. For example, materials used in additive manufacturing include plastic, metal powders, ceramics, and foundry sand. In 2012, ASTM International defined seven categories of additive manufacturing processes to group the different types of technologies (see table 1).[6]

Table 1: Types of Additive Manufacturing Processes

Process name	Description
Binder jetting	A liquid bonding agent is selectively deposited to join the powder materials.
Directed energy deposition	Focused thermal energy, such as a laser, is used to fuse materials by melting as the materials are being deposited to form an object.
Material extrusion	Materials are heated and selectively dispensed through a nozzle.
Material jetting	Materials, such as photopolymers or wax, are selectively dispensed through a nozzle.
Powder bed fusion	Thermal energy selectively fuses regions of a powder bed.
Sheet lamination	Sheets of materials are cut and stacked to form an object.
Vat photopolymerization	The use of certain types of light, such as ultraviolet light, to selectively solidify liquid photopolymers.

Source: GAO analysis of ASTM International data. | GAO-15-505SP

Note: Photopolymers are materials that transform from liquid to solid in the presence of certain types of light.

The categories of additive manufacturing systems have similarities, but there are differences in their capabilities that would affect their usage for different applications or markets. For instance, powder bed fusion and

[5]National Institute of Standards and Technology, *Economics of the U.S. Additive Manufacturing Industry*, NIST Special Publication 1163 (August 2013).

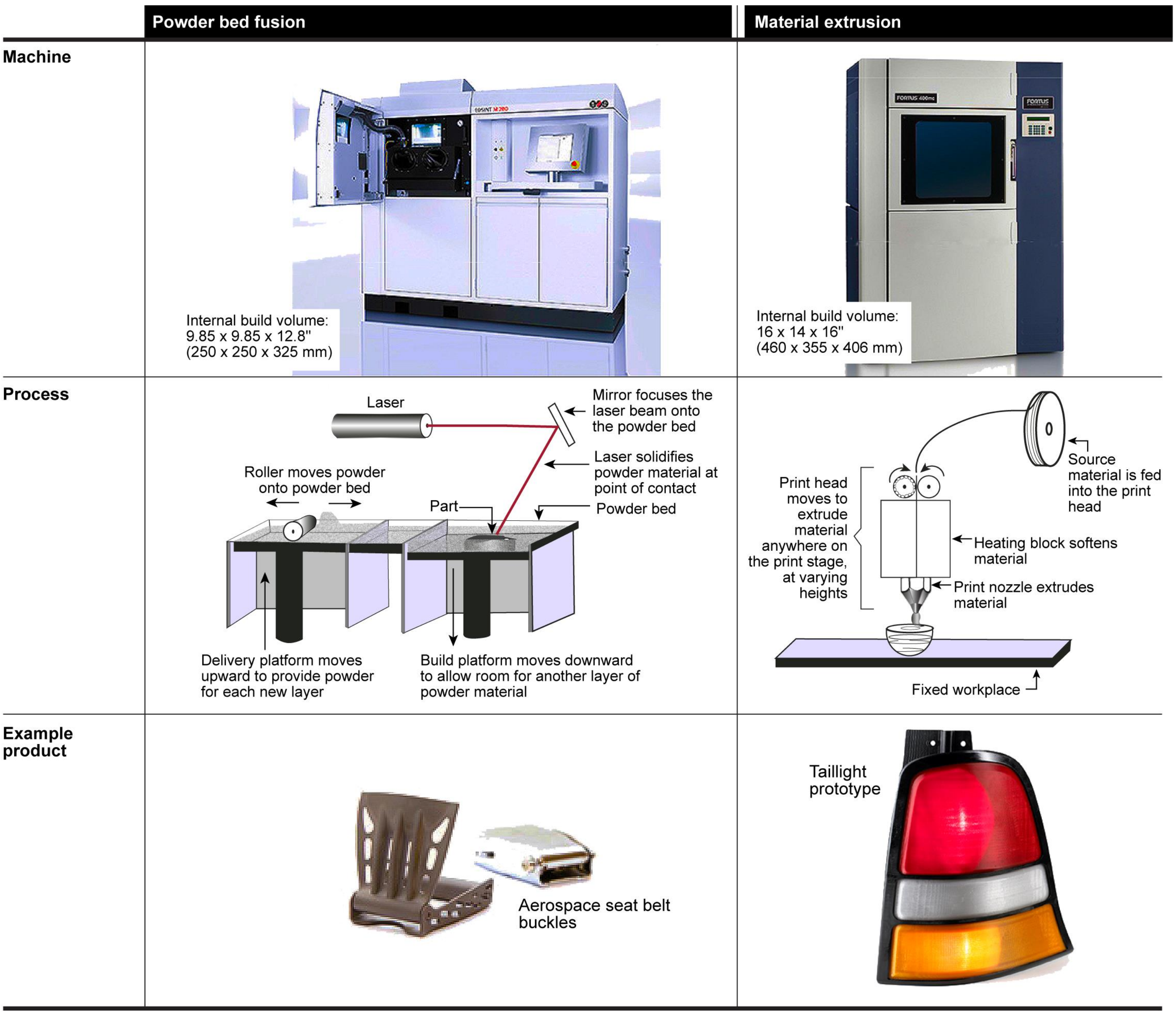
[6]ASTM International, a standards development organization, was formerly known as the American Society for Testing and Materials.

directed energy deposition both use similar energy sources, but one melts material on a powder bed, while the other melts material while depositing. Even within each category, additive manufacturing systems have different levels of capability or use different technologies. For instance, different additive manufacturing systems vary in the materials they can utilize, the speed at which they can build parts, the dimensional accuracy and quality of the surface finish of the produced parts, the material properties of the produced parts, costs of materials and machines, accessibility and safety related to complexity of operation, and other capabilities such as multiple colors.

For example, figure 2 illustrates two additive manufacturing processes, powder bed fusion and material extrusion. Powder bed fusion, here illustrated by laser sintering, can be used to produce parts from powdered materials using a laser to selectively fuse or melt the particles at the surface, layer by layer, in an enclosed chamber. The patent for laser sintering was originally filed in 1986 and forms the basis for current powder bed fusion methods. Powder bed fusion can use a variety of materials, including plastic, metal, ceramic, and glass powders, to create parts. Essentially, for each layer of the part being produced, a new layer of powder is presented to the laser. The areas that are targeted by the laser are based on each layer of the 3D digital model of the part. Machines for these processes come in a variety of sizes, with smaller units having a footprint of 2 to 3 feet wide and deep and a height of 7 feet, and larger units about the size of a small compact car. Small powder bed fusion machines can cost tens of thousands of dollars; those designed for production can range from hundreds of thousands of dollars, up to a million dollars or more. An example of a part produced by powder bed fusion using metal powder is an aircraft seat belt buckle.

An example of material extrusion is fused deposition modeling. Here, materials are heated and melted through an extruder, which acts like an automated version of a hot-glue gun used for arts and crafts. The extruder moves horizontally and vertically to deposit the material through a nozzle layer by layer. Fused deposition modeling was originally patented in 1989 and primarily uses plastic filaments as a material, but the use of metal wire as a material has been researched. Material extrusion machines range from desktop-sized design units (approximately 2 feet wide and deep) to production or large prototyping machines, which are approximately the size of a compact car. Desktop machines can be obtained for anywhere from a few hundred dollars to tens of thousands of dollars, and prototype or production machines can cost tens or hundreds of thousands of dollars. An example of a part produced by material extrusion is a taillight for an automobile. Today, most of the additive manufacturing equipment that is widely available for in-office and home environments is based on material extrusion, which has helped to contribute to the do-it-yourself or maker movement (see fig. 3).

Figure 2: Examples of Additive Manufacturing Systems



Sources: EOS GmbH (left top and bottom images); GAO (middle left and right images) and Stratasys (right top and bottom images). | GAO-15-505SP

Figure 3: Desktop 3D Printer

Source: 3D Systems. | GAO-15-505SP

Applying Additive Manufacturing to the Part Production Process

For product manufacturers, the general process for using additive manufacturing may be similar to conventional manufacturing. The product manufacturer still needs to purchase equipment for its factories from equipment manufacturers and maintain the equipment in good operating condition. Raw materials to manufacture products are still needed. Product manufacturers will employ designers that use computer-aided design (CAD) and other related tools to design products that will be sold to their customers. However, to use additive manufacturing, product manufacturers may need to design new or modify existing business processes to integrate additive manufacturing equipment into their product development process, including managing materials supplies that are compatible with their equipment. Refining these processes so that the manufacture of products using additive manufacturing systems can be cost-beneficial will be critical. As with other manufacturing technologies, the business success of additive manufacturing will be based on the ability of manufacturers to produce high-quality parts and products in a timely manner, at costs that customers are willing to pay, and that address customers' needs.

However, it is the potential ability to manufacture products outside of the factory that has contributed to the attention on additive manufacturing. As the cost of operating additive manufacturing systems decreases, and it becomes more feasible to operate and purchase such systems in multiple locations, it is possible that assembly lines and supply chains could be reduced for many parts and products. For instance, production could be moved closer to the consumer and possibly even be performed by consumers themselves. As a result, additive manufacturing could alter current structures related to production, packaging, distribution, and transportation. Further, because additive manufacturing enables the design and manufacture of custom products, it could drive the transition from mass production to mass customization, in which each produced item is customized for the consumer at little or no additional production cost.

The Federal Government's Involvement with Additive Manufacturing

Support from federal agencies, such as the National Science Foundation (NSF) and the Department of Defense (DOD), was instrumental in the early research and development into additive manufacturing. According to the Science and Technology Policy Institute, since 1986 when it first began funding additive manufacturing, NSF has expended more than $200 million on additive manufacturing research and related activities.[7] Now, several federal agencies are involved with the research and development of additive manufacturing, including NSF, the National

[7]Science and Technology Policy Institute, *The Role of the National Science Foundation in the Origin and Evolution of Additive Manufacturing in the United States*, IDA Paper P-5091 (November 2013).

Aeronautics and Space Administration (NASA), NIST, DOD, and the Department of Energy. Within DOD, several research organizations are involved, including the research laboratories of the Army, Navy, and Air Force and the Defense Advanced Research Projects Agency (DARPA). These federal agencies support research at federal laboratories, academic institutions, and small and large companies, sponsor technical conferences, and participate in standards development. To help guide research and development efforts, federal research and development agencies have supported the development of several technology roadmaps. Further, in August 2012, the National Additive Manufacturing Innovation Institute, also known as America Makes, was founded as a public-private partnership to accelerate the research, development, and demonstration of additive manufacturing and transition technology to the manufacturing industry in the United States. Its federal partners include the Departments of Commerce, Defense, Education, and Energy, NASA, and NSF. America Makes is part of a broader National Network for Manufacturing Innovation that is designed to stimulate advanced manufacturing technologies and accelerate their commercialization in the United States. The interagency Advanced Manufacturing National Program Office manages the network and includes participation from all federal agencies involved in U.S. manufacturing. It is designed to enable more effective collaboration in identifying and addressing manufacturing challenges and opportunities that span technology areas and cut across agency missions.

Federal agencies are funding a wide variety of research and development activities, including the use of new materials, processes, and applications for additive manufacturing. For instance, DOD is researching the use of additive manufacturing technology to print living cells that can form biological tissue, such as skin for the treatment of burn victims and organs for transplants. It is also conducting research to print electronic components for circuitry or antennas. The Department of Energy and DARPA have established manufacturing demonstration facilities at the Oak Ridge National Laboratory and Pennsylvania State University, respectively, to facilitate the advancement and deployment of additive manufacturing technologies. NIST is funding research into measurement science to provide greater assurance into the quality of parts produced using additive manufacturing. It is also leading efforts on additive manufacturing standards through ASTM International’s committee on additive manufacturing, which was formed in 2009. America Makes is funding research projects that are exploring the use of new materials, such as bioresorbable materials for medical devices and new metal alloys.[8]

Opportunities Exist to Use Additive Manufacturing for the Production of Functional Parts and for Other Applications

Forum participants identified many opportunities for using additive manufacturing to produce functional parts. They noted that the use of additive manufacturing has produced benefits, such as reduced time to design and produce functional parts, the ability to produce complex parts that cannot be made with conventional manufacturing processes, the use of alternative materials with better performance characteristics, and the ability to create highly customized, low-volume parts. Participants also identified some future applications of additive manufacturing, including greater use for building tooling for conventional manufacturing lines, enhancing education, and enhancing supply chain management. The maker community is also taking advantage of inexpensive 3D printing machines to produce modestly-sized polymer items. Overall, participants concluded that additive manufacturing will not replace conventional manufacturing processes, but it will be an additional tool for manufacturing parts to be used when it is appropriate from a cost-benefit perspective.

Current Applications of Additive Manufacturing Are Benefiting Industries

Forum participants identified several benefits that the aerospace, medical, and defense industries have realized from the use of additive manufacturing, including reducing the time to design and produce functional parts, whether the parts are manufactured using additive or conventional processes; producing complex parts with fewer subparts that cannot be made with conventional manufacturing processes; using alternative materials with better performance characteristics; and creating

[8]Bioresorbable materials can dissolve into the body.

highly customized, low-volume parts—all of which can lead to cost savings.

Participants highlighted various uses of additive manufacturing by the medical industry, including customized prosthetics, implants, hearing aids, and dental applications. The aerospace industry is using additive manufacturing to produce several critical parts such as ducting for in-cabin air circulation, an aircraft fuel nozzle, and a satellite propellant tank. DOD is testing the use of additive manufacturing for prototype and temporary part manufacturing in remote locations, such as aboard ships and at forward operating bases.

According to forum participants, additive manufacturing can reduce the time to design and produce functional parts because it can produce prototypes rapidly without reconfiguring or retooling the manufacturing line, and it can provide the ability to implement new concepts, designs, and innovations quickly. Overall, the use of additive manufacturing can improve the speed of getting new products to market. For example, one participant described the development of a titanium satellite propellant tank made using electron beam wire fed additive manufacturing, as shown in figure 4. Similar tanks produced using conventional manufacturing processes take about a year to design and manufacture. With additive manufacturing, it only takes about a month, reducing lead time and cost for customers. Another participant mentioned that additive manufacturing has been used for cranial implants because it can produce custom, patient-specific parts in 1 to 5 days. Using additive manufacturing also eliminates the upfront costs of tooling and molding, making it well-suited for such patient-specific parts.

Figure 4: Additively Manufacturing a Satellite Propellant Tank Using Electron Beam Technology

Source: Lockheed Martin Corporation. | GAO-15-505SP

Forum participants also described the savings from the use of additive manufacturing during the development cycle of parts produced with conventional manufacturing processes. For example, the Army's Rapid Equipping Force, which was created to provide immediate technology solutions to deployed forces, uses additive manufacturing to aid design through in-theater rapid prototyping in mobile Expeditionary Labs. These labs include additive manufacturing machines to enable Rapid Equipping Force teams to work with soldiers to quickly design and prototype solutions locally. Figure 5 shows an example of these labs. Additive manufacturing makes it easier to try a variety of designs and assess their field performance to optimize the design. For example, the Army has used this capability to design and prototype valve stem covers for a military vehicle, creating four iterations of designs to ensure fit and function, before using conventional manufacturing processes to create the final product.

Figure 5: Additive Manufacturing Systems in Expeditionary Labs

Source: U. S. Department of Defense. | GAO-15-505SP

Additive manufacturing allows manufacturers to produce some complex parts that cannot be made or are very expensive to make with conventional manufacturing processes, according to forum participants. This can enable manufacturers to create better designs that have fewer parts and use less material, which leads to reduced cost. For example, the aerospace industry is using additive manufacturing to create complex parts with fewer components than those made with conventional manufacturing. According to one participant, General Electric's (GE) use of additive manufacturing to produce jet engine fuel nozzles has allowed it to create a fuel nozzle as a single part rather than the 20 parts that would have been necessary using conventional manufacturing processes, which reduces the assembly time and costs because fewer brazes and welds are needed (see fig. 6).[9] Further, using additive manufacturing has enabled the fuel nozzles to be designed with more intricate cooling pathways and with five times more durability.

Figure 6: Jet Engine Fuel Nozzle

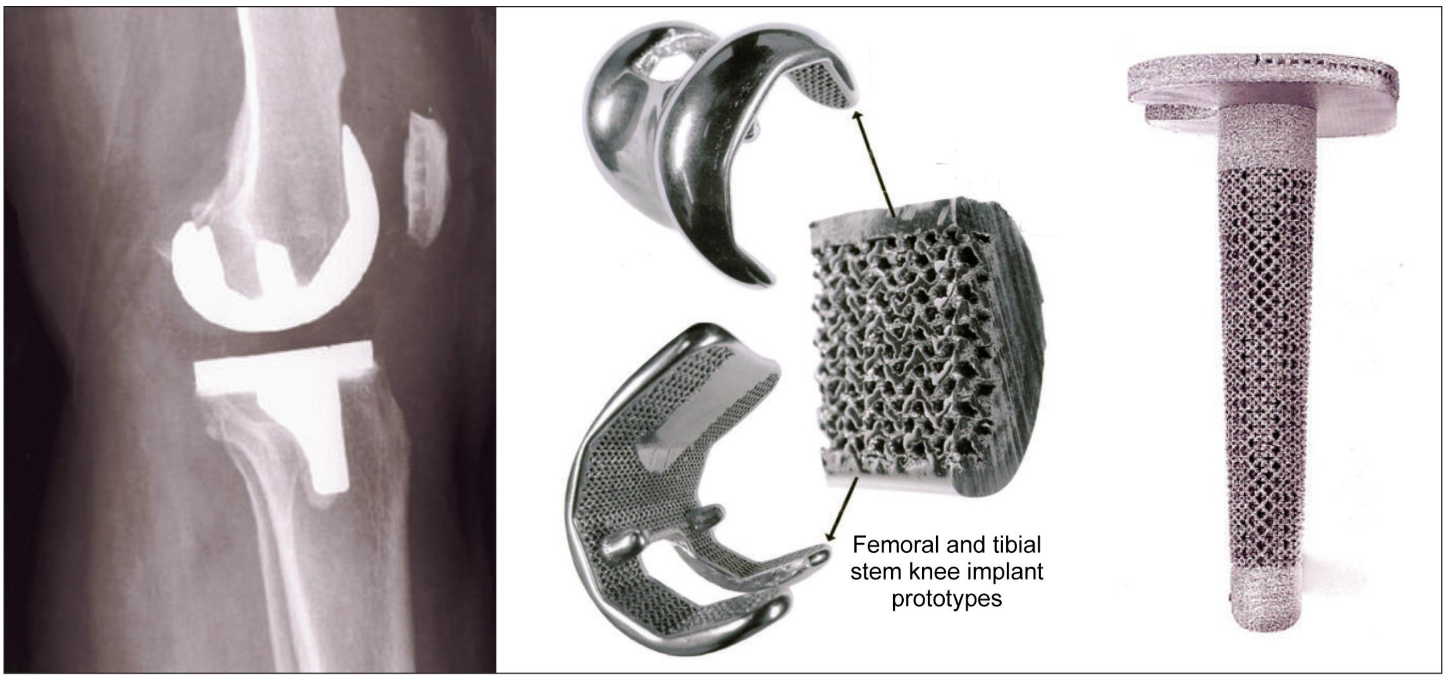
Source: General Electric. | GAO-15-505SP

Forum participants also described the use of additive manufacturing to create lighter polymer ducts for aircraft with shapes that cannot be machined or bonded together and provide a design advantage for air flow over conventionally manufactured ducts. In addition to a faster production time for the propellant tank for a satellite, participants said that using additive manufacturing has enabled a more complex tank design that can be larger than the current 47-inch diameter limitation that exists with forged die tooling. It also has fewer parts to assemble. These benefits have resulted in faster production and lower production and life-cycle costs for the satellite. Further, overcoming the forged part design limitation means that different sizes and geometries can be explored for future designs. For medical implants, complex internal mesh structures

[9]A braze is a soldered joint between metal pieces.

and porous structures enable bone to grow into the implant for better integration, as well as the ability to vary the density to more closely match the stiffness of the surrounding bone. Figure 7 shows an additively manufactured prototype tibial and femoral stem knee implant demonstrating the complex internal structure and porous surface achievable using additive manufacturing along with an x-ray of a knee implant in place to show how they would be used.

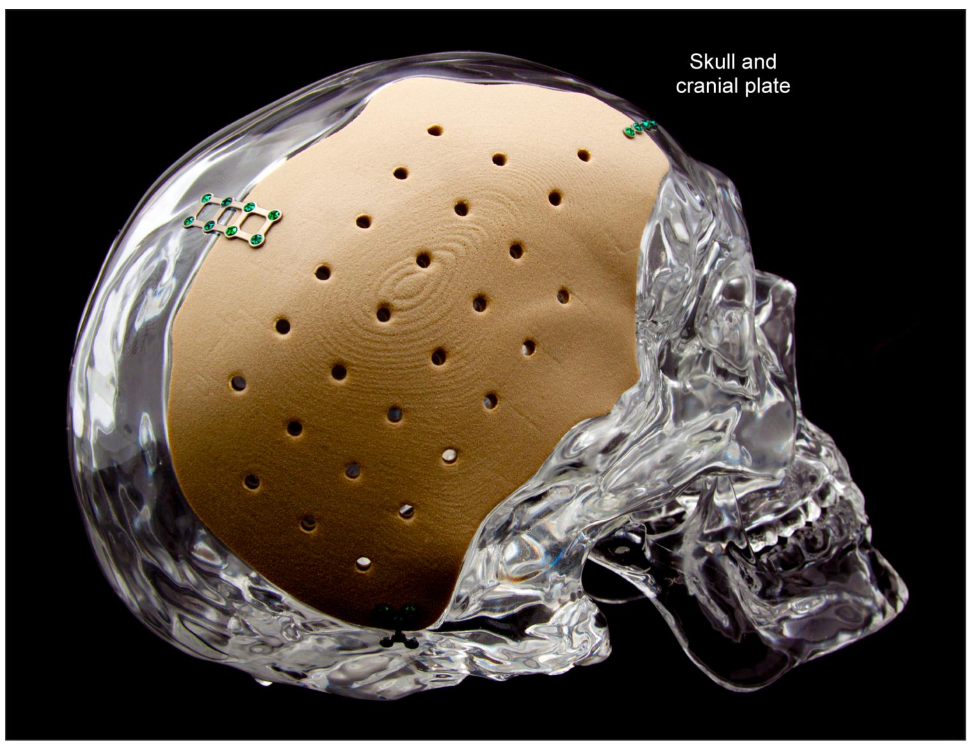
Figure 7: Complex Internal Structure of a Knee Implant



Source: Dr. L. E. Murr, University of Texas at El Paso. | GAO-15-505SP

Forum participants said that additive manufacturing also enables the use of alternative materials for parts that may result in better performance than equivalent parts manufactured using conventional materials, such as lower weight and greater strength. Several participants identified examples in the aerospace industry of lighter parts when using additive manufacturing instead of conventional manufacturing. For instance, one participant described the substitution of polymers for metal in aircraft ducts that results in lighter parts, which, over the lifetime of the aircraft, will reduce operating costs as a result of reduced fuel consumption. While using additive manufacturing to create the parts may sometimes cost more, overall cost savings can be achieved through simplified assembly due to fewer parts and reduced production and repair times. One participant provided an example of an airline using additive manufacturing to produce an arm to hold video monitors for its aircraft. While it cost more to produce these parts compared with using conventional processes, the parts incorporated an internal lattice structure, resulting in less material used and, therefore, less weight, resulting in an estimated savings in fuel use of more than $1.5 million over the life of the aircraft. Using additive manufacturing to create the aircraft engine fuel nozzles has enabled the use of an alloy material that is light, strong, and corrosion resistant and can operate at a 20 percent higher temperature than their conventionally manufactured counterparts. These additively manufactured nozzles weigh 25 percent less than their predecessor parts, reducing fuel costs. Another participant described an example of a cranial implant, which has been approved by the Food and Drug Administration, using a high-performance plastic material that is lighter than conventional materials with similar density and stiffness to bone and unlike conventional materials, such as titanium and stainless steel, does not interfere with diagnostic imaging equipment. Figure 8 shows an example of a plastic cranial implant.

Figure 8: Custom Patient-specific Cranial Implant



Source: Oxford Performance Materials, Inc. | GAO-15-505SP

Forum participants said that one of the other key benefits of additive manufacturing is its use to create highly customized, low-volume parts quickly and at lower costs than using conventional manufacturing to produce comparable parts. For example, participants said that manufacturers in the medical industry are using it to produce customized prosthetics and implants faster and more cheaply. Using additive manufacturing enables each part to be made specifically for the individual patient’s anatomy, which results in a better fit and an implant that is more structurally sound for a longer period of time, which, in turn, leads to better medical outcomes with fewer side effects. Prosthetics can also be customized for functionality to meet the patient’s needs. Participants also stated that using additive manufacturing can result in easier and shorter surgeries. For instance, customized models and surgical guides enable surgeons to execute the treatment plan before the surgery, which reduces surgical time while also improving surgical outcomes.[10] One participant indicated that DOD has seen reductions of one-quarter to one-half of the time needed for surgery due to customization. Reducing the amount of time to perform surgeries can result in significantly reduced surgical costs, which, according to one participant, can be up to $300/minute.

Forum Participants Highlighted Some Future Uses for Additive Manufacturing

Forum participants indicated that, while the future use of additive manufacturing is uncertain, it is expected to expand in both existing and new applications, such as tooling for conventional manufacturing lines, enhancing education, and supply chain management. Additive manufacturing is already used for tooling, and some participants said that there is great potential for further growth to build tooling for conventional manufacturing lines, such as for stamping dies to make sheet metal parts for the automotive industry or to make custom molds for metal casting or plastic injection molding. However, one participant stated that, while additive manufacturing would work technically for producing tools, it would only be economical to produce high-performance tooling. Similar to functional part production, additive manufacturing enables the production of more complex tool designs with different geometric features

[10] A treatment plan describes a patient’s condition and necessary procedures, including details of the treatment to be provided, the expected outcome, and the expected duration of the treatment.

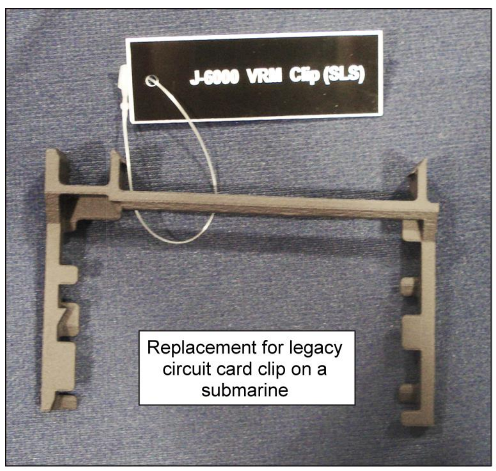
incorporated into the tooling to change the characteristics of the end products, such as the surface finish or structure. Additionally, tools can be manufactured in less time and with reduced downtime for production, and the process may reduce the cost of tool production, and result in tools of higher quality.

Forum participants identified the use of additive manufacturing by teachers and instructors to enhance education as a key future use. The use of 3D printers to create teaching tools can improve lesson planning so that students can grasp concepts better and see real world applications of what they are learning and become more engaged. Additive manufacturing also can be used to create visual tools that enable students to visualize information in a way that is easier to comprehend and retain. New capabilities for 3D visualization of ideas could lead to a new generation of designers, engineers, scientists, and doctors.

According to forum participants, additive manufacturing will change supply chains, but it is not certain how or to what extent. It is unclear what parts will be printable in the future or how such manufacturing will affect the boundary between manufacturers and customers, as customers could become their own manufacturers for some types of parts. For instance, the maker community is growing exponentially and is already taking advantage of low-cost additive manufacturing machines to design and manufacture low-volume customized niche products and selling them over the Internet. It can also provide the capability to create mass-customized components, such as shoes, shells for cell phones, or other consumer items. Additive manufacturing enables parts to be built locally as needed, reducing the need for manufacturers to produce minimum lots and to ship and store material, which could make inventory forecasting more accurate and reduce financial constraints.

For example, participants stated that DOD is looking at ways to use additive manufacturing in supply chain management, including using it to repair equipment and produce parts in the field to reduce the need to store parts, to produce discontinued parts or temporary parts to use until a permanent part can be obtained, and to quickly build parts to meet mission requirements. This will enable personnel in the field to repair equipment, reduce equipment downtime, and execute their mission more quickly. Figure 9 shows some of the simple parts that could be additively manufactured in the field. One participant mentioned that one of the key DOD uses could be in supply depots and how inventory is managed in them and cited a prior GAO report on the topic. In December 2008, we found that the Navy had about $7.5 billion in inventory exceeding requirements,[11] and some participants indicated that the ability to additively manufacture parts on-demand could help reduce this inventory. Some participants stressed that additive manufacturing may reduce the need to stock spare parts, but it will not eliminate this need because many parts cannot be made through this process or cannot be made cost-effectively. The Army and Navy are exploring the use of additive manufacturing in the field and have experimented in making small parts, such as valve stem covers for vehicles and onboard logistics parts for ships that were difficult to locate such as drain and valve covers. The Marine Corps is just beginning to plan and evaluate the use of additive manufacturing. According to one participant, during the Marine Corps's annual Expeditionary Logistics Wargame, a vendor demonstrated the use of additive manufacturing to repair small broken parts for an explosive ordinance robot using additively manufactured parts.

Figure 9: Simple Additively Manufactured Replacement Parts



Source: U. S. Department of Defense. | GAO-15-505SP

According to forum participants, while the use of additive manufacturing will grow in the future, it will not replace conventional manufacturing processes, but it will be an additional tool for manufacturing parts to be used, when appropriate, from a cost-benefit perspective. In many circumstances, conventional processes for manufacturing parts will always be faster, better, and more economical for extremely high-volume

[11]GAO, *Defense Inventory: Management Actions Needed to Improve the Cost Efficiency of the Navy's Spare Parts Inventory,* GAO-09-103 (Washington, D.C.: Dec. 12, 2008).

and well-proven parts. Additive manufacturing will likely be best for parts requiring properties and features not achievable through conventional manufacturing or for low-volume parts, such as custom items and tooling. One participant provided the example of producing titanium compressor blades for aircraft turbine engines. Millions of these blades are made every year using conventional processes, and additive manufacturing cannot compete with the efficiency and cost of these processes. Additive manufacturing can be integrated into the manufacturing process as a whole, such as using it for further processing of parts manufactured using conventional processes. Additive manufacturing can also be used to repair parts produced using conventional manufacturing processes. For example, one participant talked about using an additive manufacturing process called directed energy deposition—which enables the creation of parts by melting material as it is being deposited—to repair aircraft turbine blades rather than replacing them with new blades.

Industry Faces Key Challenges in Using Additive Manufacturing to Produce Functional Parts

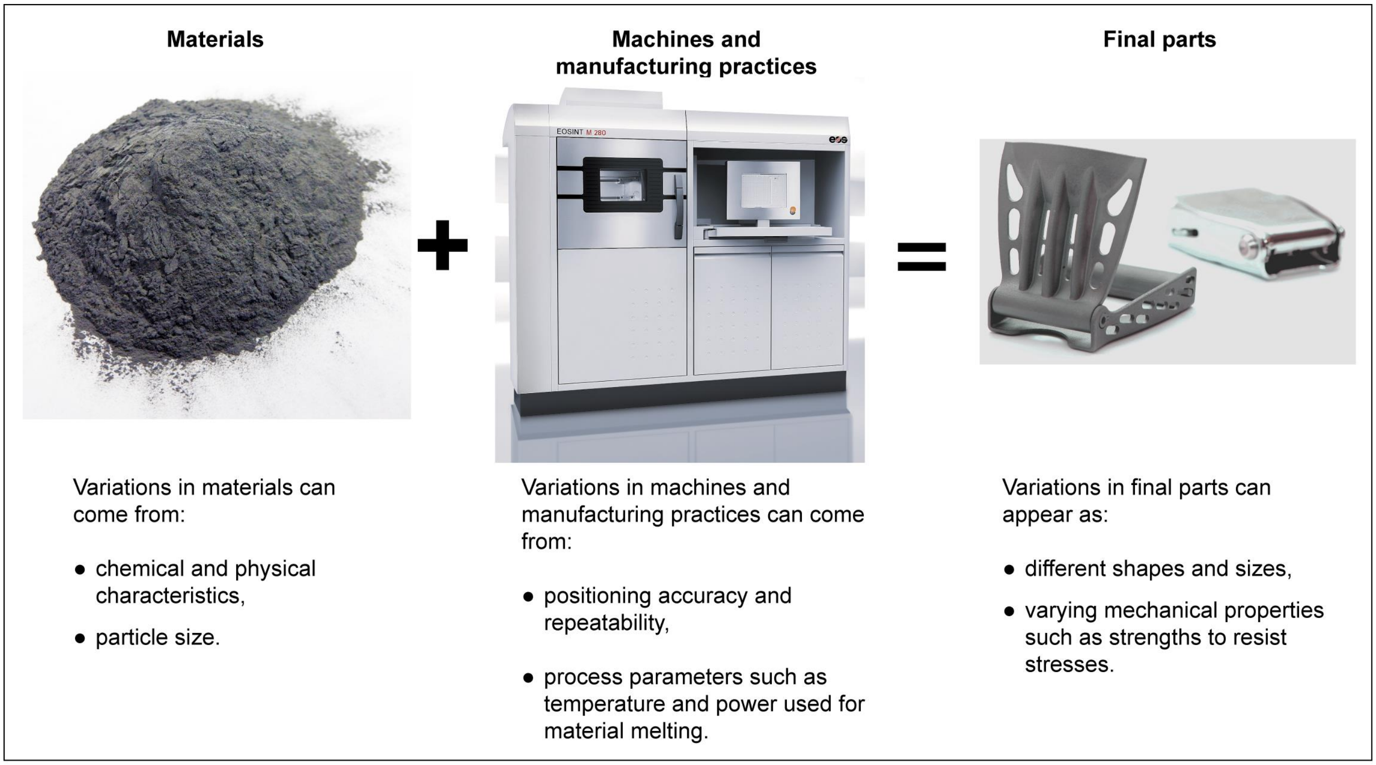
Forum participants identified challenges in using additive manufacturing to produce functional parts. These challenges can be broadly grouped into three main areas: (1) ensuring product quality, (2) limited design tools and workforce skills, and (3) supporting increased production of functional parts, such as the need for a more robust industrial infrastructure. Appendix IV provides the full list of challenges identified by the participants during the forum meeting.

Additive Manufacturing Faces Challenges in Ensuring the Quality of Functional Parts

Forum participants identified the need to ensure the quality of functional parts, such as ensuring that manufacturers can repeatedly make the same part and meet exactness and consistent performance standards on the same machine or on different machines, as a key challenge. Additive manufacturing has historically been used to create prototypes that do not need to meet the same level of quality as final products and may not need to be exactly reproduced multiple times. However, as the technology is increasingly used to directly manufacture functional parts and competes with established manufacturing processes, the additive manufacturing industry needs to improve its ability to ensure product quality, according to the participants. This becomes particularly important for the medical, aerospace, and defense industries, where products must consistently meet high quality standards to be usable.

The quality of functional parts produced using additive manufacturing depends on a variety of factors. One participant highlighted several potential sources of variability that could affect product quality, including materials, machines, and manufacturing practices (see fig. 10). Current technology and practices do not ensure that these sources of variability can be consistently controlled to produce the desired product. For example, if manufacturers take a commercially available material (typically a powder) and use it in a commercially available machine, they would not be assured of consistently making the same product and having it consistently meet quality standards because variability in any of the elements of the manufacturing process could result in a final product that does not meet standards. For example, one participant said that these machines have different settings that can be used during production and that different manufacturers may set their machines up differently to create a part.

Figure 10: Examples of Variability in Additive Manufacturing Materials, Machines, Manufacturing Practices, and Final Parts



Sources: GAO (analysis), University of Louisville Rapid Prototyping Center (left image), EOS GmbH (center and right images). | GAO-15-505SP

Currently, additive manufacturing machines, particularly metal-based machines, can have difficulty maintaining the quality of final parts because there are sources of variability that affect the machines' ability to control the additive manufacturing process. For example, uneven temperature in certain types of additive manufacturing machines during production can lead to inconsistent dimensions and mechanical properties, such as strength, impact resistance, or hardness, in the resulting functional parts. These inconsistencies may lead to some parts not performing as intended. Another participant emphasized that the machines themselves are constantly evolving and improving, which creates another challenge in gaining control of the process. To address this challenge, participants said that manufacturers need better methods to control the additive manufacturing process to achieve high quality, including tools focused on measuring and controlling the additive manufacturing process. For example, a few participants mentioned the possibility of incorporating real-time monitoring systems into additive manufacturing machines to check the quality of each layer put down by the machine. One participant noted that some machines have limited monitoring systems now and that those systems could be expanded in the short term.

Forum participants said another challenge to ensuring the quality of functional parts produced is limited knowledge of additive manufacturing material properties. Specifically, manufacturers need to understand how a material will perform during processing and how the material's properties will affect the quality of the final part. Understanding material properties requires conducting research and developing material properties databases, which can be used to determine whether a part made from a specific material will meet quality requirements. For example, making products with high quality requirements, such as cranial implants that are customized to specific patients, requires a high degree of control of the material, according to one participant. Maintaining a high degree of control requires manufacturers to have a strong understanding of the material's underlying properties, as well as how variations in process influence the mechanical properties of the final part. As another participant explained, these material properties databases can provide the customer using the final product with a greater level of confidence and also help lower risks of using the product.

The additive manufacturing industry also needs to develop an improved suite of standards related to different elements of the additive manufacturing process, according to participants.[12] The industry has been developing a supporting body of knowledge for the technology over the past 3 decades, but that is not much time compared with conventional manufacturing processes, according to some participants. For example, the additive manufacturing industry has only been developing standards since about 2009, and several participants said that further standards are needed. One participant noted that the standards related to 3D building, including standards for geometric accuracy and surface characteristics, are not well-defined. Controlling machines to ensure reproducibility can take a great deal of time and expertise. With well-developed standards, manufacturers can have a more consistent approach to collect and report test data to ensure product quality. Moreover, standards development

[12]Standards include common and repeated use of rules, conditions, guidelines, or characteristics for products or related processes and production methods, and related management systems practices. As of March 2015, ASTM International had 11 standards for additive manufacturing in design (1), materials and processes (6), terminology (1), and test methods (3).

could help reduce variability in additive manufacturing processes, such as how machines are configured, maintained, and operated. Developing additional standards also could improve the confidence of product manufacturers, small- and medium-sized companies considering using additive manufacturing, and the customer using the product by providing a common understanding of how the product was manufactured and how it should perform. Such standards will be important to the development of the industry. However, one participant noted that the industry does not need to start from scratch because manufacturers will be able to make some use of the existing standards.

Participants stated that additive manufacturing needs to improve its ability to meet certification requirements. Certification by an independent body can be used to show that a product meets quality requirements and customers[13] or regulators[14] in certain industries may require that products meet specific standards. For example, additive manufacturing companies seeking to manufacture and sell safety critical airplane parts, such as engine parts, to aerospace companies must be able to have the manufacturing processes and parts certified. In order to facilitate this process, participants agreed that additive manufacturing needs consensus methods[15] and test data for qualification[16] of materials and production processes leading to certification of the final products.

Before a product can be certified, manufacturers must qualify the materials and processes used to make the part, which involves manufacturers conducting tests and collecting data under very controlled

[13]For example, DOD requires parts it purchases, such as aircraft engine parts, to meet specific standards or performance criteria. Manufacturers might need to have these parts certified to meet DOD's standards.

[14]For example, the Federal Aviation Administration sets standards in its regulations for safety critical airplane parts, such as engine parts. Manufacturers must certify that any safety critical parts meet these standards by having them certified.

[15]Consensus methods are standard testing methods that could be applied across the additive manufacturing industry and used in the qualification and certification process.

[16]Qualification processes are used to determine whether a product, process, or system meets a set of established requirements. Materials and processes used to produce critical components for applications in the defense, aerospace, and medical industries must be formally qualified before the components can be certified. Extensive empirical testing to fully qualify a material often requires conducting thousands of tests, costing millions of dollars, and taking years to complete.

conditions. Other manufacturing processes have established methods and data based on a long history of use, but additive manufacturing does not have this support. For example, reliable databases of material properties are not generally available for additive manufacturing and are necessary for qualifying materials. By contrast, materials data to support other manufacturing processes, such as injection molding, are available to manufacturers. However, participants noted that qualifying new materials and processes is a time-consuming and expensive process, potentially taking several years. Improved consensus methods and test data could make the qualification process more efficient. In addition, one participant said that it can be challenging to qualify additive manufacturing processes because the machines are regularly being revised, and minor changes to a process can require requalification.

In order to certify the final product, manufacturers will need ways to test it to ensure that it meets established standards. Current testing methods are not always well-suited for additive manufacturing. For example, some commonly used testing methods destroy a given number of parts or test pieces to confirm that they meet established standards.[17] One participant noted that this type of testing requires destroying a lot of parts to ensure that those being manufactured for the customer have sufficient quality, which adds to the total costs of the final product. Another participant emphasized that developing better alternatives to these destructive tests have the potential to facilitate the certification process. In addition, improved nondestructive test methods could provide a more effective way to validate that a unique part, such as a cranial plate for a patient, was made correctly without having to destroy extras. Current inspection methods work very well for conventional products, but may not work as well with additive manufacturing, according to one participant. For example, specialized tools designed to measure the dimensions of a

[17]The destructive testing approach involves testing a statistically representative sample of parts to determine whether they meet product requirements as well as for reliability and durability. For example, destructive testing is often used to determine the physical properties of materials, such as impact resistance. This testing is more commonly used in high-volume production where the loss of a set number of parts for testing is not a substantial cost.

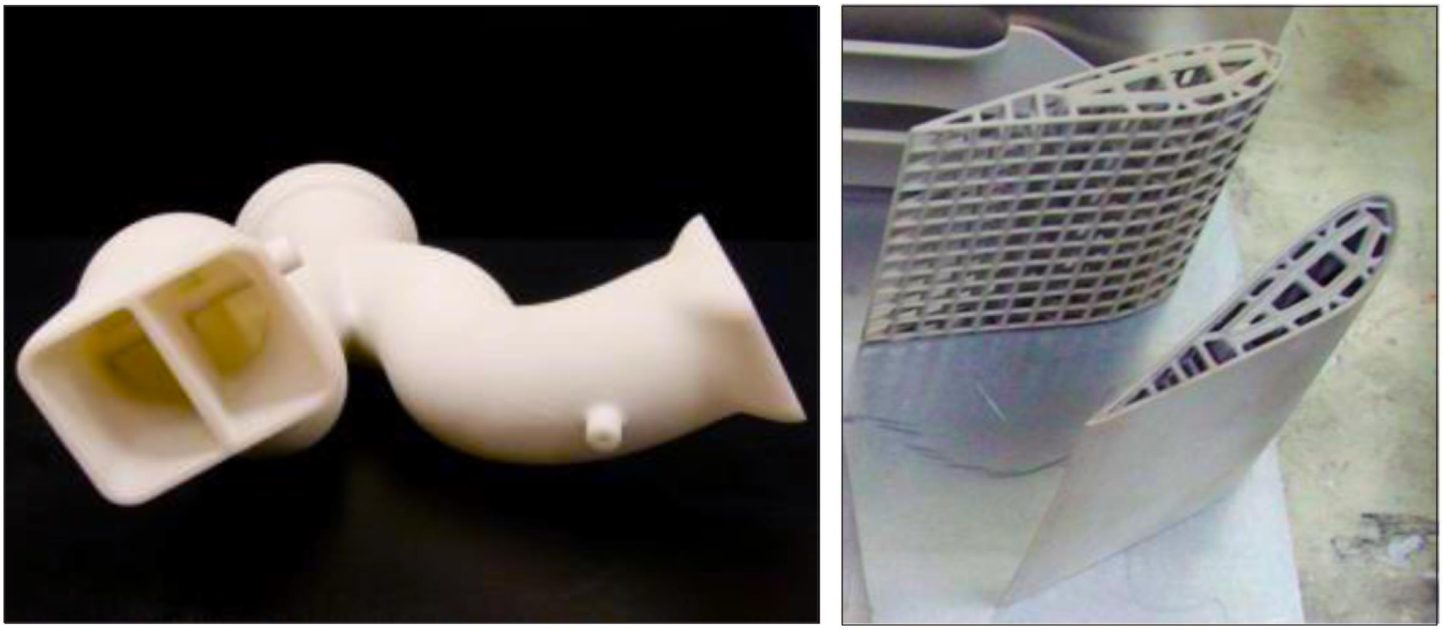
product may not fit as well into complex shapes or internal passageways and will not be as accurate for inspecting product quality.[18]

Additive Manufacturing Faces Challenges from Limited Design Tools and Workforce Skills

Forum participants said that existing design and analytical tools combined with an insufficiently skilled workforce could limit the use of additive manufacturing and its ability to reach its potential for greater innovation. As previously noted, building products with customized shapes is one of the potential benefits of using additive manufacturing compared with conventional methods (see fig. 11 for examples), but existing CAD software limits the ability of designers to explore new possibilities. For example, one participant noted that it is difficult for designers to fully use complex geometrical shapes such as ovals, mesh, or empty spaces using existing CAD software. CAD software designed to take advantage of additive manufacturing's capabilities would have clear advantages for designers, but one participant pointed out that there may not be enough incentive for CAD software developers to fully incorporate functionality to utilize all of the capabilities of additive manufacturing when it is a small part of the overall market.

[18]Specialized tools, such as touch probes, are designed to measure component surfaces, providing accurate, geometric data. Obtaining and analyzing these data throughout the manufacturing process can help to ensure components remain within conformance limits.

Figure 11: Examples of Additively Manufactured Products with More Complex Shapes (Aerospace Duct (left) and Trussed Air Foils (right))



Sources: 3D Systems (left) and Lyons, B., The Boeing Company (right). | GAO-15-505SP

Participants agreed that designers also will need tools capable of analyzing the products designed specifically for additive manufacturing to complement new CAD design tools. For example, if new CAD software allows designers to make use of complex geometrical shapes, tools are needed to analyze these new shapes. According to one participant, the product needs to be checked to show that it can meet functional requirements, such as whether the product has sufficient strength or resistance to impact. Another participant emphasized that analysis will be critical for any engineered products with specific quality requirements that are made with additive manufacturing. A challenge in developing analytical design tools involves developing the capability to measure and model the additive manufacturing process and then predicting how the process will affect the quality of the final product, according to participants. Specifically, designers require an improved understanding of how different elements of the additive manufacturing process, such as materials, machines, and manufacturing practices, affect product quality. In addition, analytical tools for additive manufacturing will need to integrate various components into a systematic approach to designing and engineering products for additive manufacturing including engineering analytical methods and test data on various material properties, one participant said. Developing this capability will require further research, according to participants.

Participants also emphasized the value of developing a skilled workforce capable of thinking differently about design to take full advantage of additive manufacturing. Some participants pointed out the importance of having designers who can utilize the capabilities of additive manufacturing, such as building a product as one piece instead of building multiple pieces and assembling them into a product. One participant cited the GE jet engine fuel nozzle that the company decided to build using additive manufacturing. The initial design approach involved developing multiple CAD designs for separate components of the nozzle and then assembling the components, which is a traditional manufacturing approach. However, one engineer brought up the idea of manufacturing the entire product as one piece, which takes advantage of additive manufacturing's capabilities more fully. The design team switched to this approach and is moving forward with developing the part. Participants noted that retraining the manufacturing workforce to think differently about design will be an important part of building skills, including retraining experienced engineers who may be challenged by changes in traditional methods.

Designing for additive manufacturing also involves working across multiple disciplines to develop products. Several participants mentioned the importance of integrating skills from different disciplines into design for additive manufacturing, including science, technology, engineering, arts, and mathematics (STEAM). A workforce that can cross disciplinary boundaries, such as materials science, mechanical engineering, and manufacturing engineering, will be a key for additive manufacturing design, according to participants. For example, to develop products for additive manufacturing, a company may need a chemist who can relate to and work with materials specialists as well as be able to incorporate ideas from digital design into their work. In addition, some participants said that the kind of open-ended and creative thinking that is used in the arts will likely have value for the additive manufacturing workforce. For example, one participant said incorporating people with an arts background into design would be valuable because they think in fundamentally different ways than engineers and might use CAD software differently. Another participant noted that individuals from nonengineering backgrounds, such as graphic designers, often make very good designers for additive manufacturing.

Several participants said that the technology should be incorporated into educational and workforce training curricula because it can help prepare the future workforce. Following are examples:

- According to some participants, additive manufacturing should be incorporated into education from kindergarten through 12th grade to help engage students with the technology. This early engagement helps to build the pipeline of talent for the future workforce, according to participants.
- Several participants noted the importance of improving education at the university level. Participants said there are an increasing number of additive manufacturing degree programs, but some said a degree focused on additive manufacturing might not include the underlying skills needed to fully utilize the technology. One participant suggested that additive manufacturing should be incorporated into the existing curricula for traditional STEAM disciplines as well as into disciplines like medicine and law because the technology is likely to be extensively used across society.
- Participants also said that training in additive manufacturing could be a part of nondegree programs or 2-year technical degrees. For example, one participant said there is an opportunity for programs to train individuals to use additive manufacturing to fabricate items for medical professionals, such as models or guides for surgeons. Training individuals to use the technology for specific applications like this can be done in a matter of weeks as opposed to the more intensive training and education needed to learn to design for additive manufacturing, according to the participant.

The Additive Manufacturing Industry Faces Other Challenges to Supporting Increased Production of Functional Parts

Forum participants identified several other challenges the additive manufacturing industry faces in supporting increased production of functional parts. Specifically, participants agreed that the additive manufacturing industry needs a more robust industrial infrastructure, including stronger supply chains and better access to financing. The industry relies on sometimes limited supply chains for machines and materials, which can pose a challenge to the increased use of additive manufacturing for functional part production. For example, one participant mentioned an industrial accident at a facility that was the sole supplier of a nylon powder used in additive manufacturing machines. When that facility stopped producing material, there was nowhere else to get that powder, so the production of parts using that powder stopped. The robustness of a material supply chain depends on the material itself. For example, some metal-based additive manufacturing machines use metal welding wire, and there is a robust supply chain for that. However, more unique additive manufacturing materials, such as metal or nylon powders, typically have less robust supply chains.

Participants also expressed concerns about the robustness of the supply chain of additive manufacturing machines. One participant said that rapid growth of additive manufacturing has put pressure on the industry's supply chains to support that growth. As the industry continues to grow, there is a concern that the infrastructure may not be able to support that continued growth. For example, a participant mentioned an additive manufacturing company that is bidding on a major production contract to help the bidder transition from prototyping into direct functional part production. A company leader voiced concern that there may not be a reliable supply of additive manufacturing machines to meet the contract, meaning they would take a risk in bidding for the contract. Limitations on the supply of machines also can make it difficult for companies to scale up production, another challenge mentioned by participants, because producing larger volumes of parts can require many additive manufacturing machines. These supply chain challenges make using additive manufacturing to produce functional parts a potential risk for a project. These risks can hinder further adoption of additive manufacturing by managers who are focused on meeting schedule, cost, and performance requirements.

Participants noted challenges with obtaining financing for capital investments in additive manufacturing machines, which can be expensive.[19] One participant said the financing problem involves a misunderstanding of additive manufacturing compared with other manufacturing processes. For example, the participant said that, when considering an investment in a more established type of conventional manufacturing machine, he could calculate when that machine would start producing revenue based on how many parts it could produce in a given time period. However, with additive manufacturing machines, the

[19]Additive manufacturing machines for industrial use can range in cost from hundreds of thousands of dollars to a million dollars, or more.

fabrication speed—the time it takes for an additive manufacturing machine to build a given part—can be much slower than other manufacturing processes. As a result, the additive manufacturing machine may not appear to be a good investment when compared with an investment in a conventional manufacturing machine. However, this approach may not take into account some potential advantages of the additive manufacturing technology, such as the ability to manufacture small numbers of highly customized items such as prosthetics or its inherent flexibility. Several participants agreed that there needs to be a better understanding of the technology and its implications among financial stakeholders.

Several participants also highlighted the importance of understanding when additive manufacturing can be used cost-effectively. Participants agreed that additive manufacturing will not be the best process for every situation. To inform decisions about whether to use additive manufacturing, companies and other potential users need to analyze the costs and benefits of using the technology. Among things that would be helpful to consider, participants said, are cost models and life-cycle costs related to additive manufacturing. These decision-making tools can help potential users of the technology, such as project managers, better understand the risks and benefits of using additive manufacturing considering their schedules, costs, and performance goals. These decisions are particularly important for small- and medium-sized companies, which have more limited resources to take risks than large companies. Combined with other industry challenges, such as availability of materials and skilled workers, there are notable barriers to adopting additive manufacturing for small- and medium-sized companies, one participant said.

Participants identified the technical capabilities of additive manufacturing as challenges to supporting the technology's increased production of functional parts. For example,

- Several participants said that, compared with established manufacturing technologies, additive manufacturing has a limited set of materials that can be used to produce functional parts. In addition, the industry needs to design materials for additive manufacturing that are specially suited to new products. For example, one participant highlighted that additive manufacturing allows a greater level of customization in the medical device industry than previously available, including designing what the surface of a product should be like or how tissue can adhere to it. However, medical device companies looking to use additive manufacturing do not currently have the necessary materials to fully implement this potential level of customization.

- Another technical capability that is a challenge involves the ability to build larger and smaller products. For example, most additive manufacturing machines have a desktop-size building space, according to one participant, and that limits the ability to build large products.[20] On the other hand, improving the ability to do very small-scale manufacturing with the machines, such as laying down functional electronic circuitry, would be important.
- Participants identified fabrication speed as a challenge to increased production. For example, at current fabrication speeds, constructing a part can take hours or even days, compared with much shorter times for other manufacturing processes. That said, in select circumstances, additive manufacturing can reduce overall manufacturing times compared to conventional manufacturing.

Several participants commented that improving the technical capabilities of additive manufacturing can be accomplished with more research and development, much of which is under way.

Participants identified challenges related to coordination and information sharing among those involved with additive manufacturing technology. For example, participants generally agreed that more research and development will be needed to advance additive manufacturing and increase its use in making functional parts. However, they identified challenges related to coordination of research and development necessary to make these advances. For example, some participants expressed concern over uncoordinated duplication of research efforts, such as redundant efforts to create material properties databases. However, other participants pointed out that duplication of research can have value at this stage in additive manufacturing's technical development if it is used to validate previous findings, a key step in the scientific process. While participants generally agreed that more research and development is key to addressing the technical challenges of additive manufacturing, several expressed concerns that the industry will have difficulty coordinating this research and development because research

[20]Participants said that machines with larger capacity exist, and that even larger ones are under development. However, most of the available machines have a relatively limited building space.

findings can lead to a competitive advantage in the marketplace. Research on additive manufacturing, such as collecting data on material properties, represents potentially valuable proprietary information for companies that they may not want to share. Several participants agreed that identifying areas where information could be shared and not lead to a competitive advantage (also called precompetitive research) would be beneficial to the industry, but that doing so would be difficult and requires substantial coordination.

Key Considerations for Federal Policy Actions That Could Affect the Future Use of Additive Manufacturing for Production of Functional Parts

Forum participants identified three key areas that federal policymakers would need to consider before taking any policy actions that could affect the future use of additive manufacturing for production of functional parts: (1) key challenges facing the industry, (2) areas that could be affected by an increased use of additive manufacturing, and (3) trade-offs of any potential actions. There was no consensus on specific policy actions needed, but participants discussed a variety of policy approaches that the government could consider, including encouraging a national dialogue about the government's role.

Participants Highlighted Key Industry Challenges That Could Benefit from Government Involvement

As we discussed previously, the additive manufacturing industry faces several challenges to support increased production of functional parts and forum participants stated that all of these challenges could benefit from increased government involvement. The three key areas identified by participants as the most important for federal involvement are: (1) standards setting, (2) workforce and training, and (3) market support and readiness.

Forum participants said that if federal actions focused on standards setting, they could encourage increased use of additive manufacturing. Participants discussed the federal government's roles as both an entity that develops and applies measurements and standards and as a consumer of additively manufacturing goods with specific requirements.

One forum participant emphasized the importance of establishing standards by describing them as the ground rules for opportunities in the sector. The federal government, primarily through NIST, currently plays a role in setting standards and requirements for additive manufacturing in collaboration with industry-led standards developing organizations, such as ASTM International. However, one participant said that the process is slow, and the work is generally done by a volunteer workforce from government, industry, and academia. Participants suggested that the government could be a catalyst to provide momentum to get more participants involved in standards setting. In some cases, not enough is known about the processes and materials used in additive manufacturing to establish standards, so NIST conducts research in four key areas: (1) characterizing materials and mechanical properties of manufactured parts, (2) creating standard methods for measuring and improving process repeatability and accuracy, (3) developing fundamental data and methods for qualification of processes and parts, and (4) conducting system analysis of the entire additive manufacturing information flow from beginning to end.

According to forum participants, government consumers, such as DOD and NASA, have specialized missions with unique product reliability requirements. Both agencies are interested in the potential use of additive manufacturing, but using additively manufactured products in their missions will be challenging because they require assurances of both the consistency and quality of any products they use. A forum participant stated that DOD has an ongoing project to develop products using additive manufacturing, which has required a redesign of some of its process steps to accommodate its needs for quality inspection using nondestructive methods. Participants also cited other areas of ongoing work at regulatory agencies, such as the Federal Aviation Administration and the Food and Drug Administration, to ensure that additively manufactured goods are capable of meeting their quality and performance requirements.

In addition to standards setting, forum participants emphasized the importance of federal actions in the area of workforce education and training. Participants frequently mentioned the need for engineering and technical education programs to increase their focus on design education. Additive manufacturing fundamentally restructures the possibilities of manufacturing, and forum participants said that a workforce capable of design-focused thinking is important to additive manufacturing’s success. Federal agencies currently play a significant role in developing the capabilities of the U.S. workforce through numerous programs to support science, technology, engineering, and mathematics education. A forum participant noted that a recent GAO report identified over 200 federally-funded science, technology, engineering, and mathematics programs.[21] Federal agencies also have programs that support education in the arts and design. Forum participants noted that adding design thinking into more traditional disciplines could be beneficial to the sector. One participant described the current education and workforce development situation as the "Wild West" and discussed the need for an education organization and coordination plan for the United States with a goal of improving the situation. Another participant suggested that other organizations along the public-private partnership spectrum might be able to help coordinate education and workforce issues. Another forum participant discussed the need for directed workforce training efforts and suggested a role for community colleges and vocational/technical schools.

Forum participants identified additive manufacturing market support and readiness as the third key area of federal action needed to support the production of functional parts in the United States. A participant suggested looking at the federal acquisition strategy and determining where it would be possible and practical to make spare parts by additive manufacturing. A participant described this as an investment in the future of the technology in the federal acquisition system. In addition to its function as a consumer, the federal government works to integrate U.S. companies with existing public, private, or not-for-profit industrial and economic development resources. Currently, this is done in partnership with America Makes, which has a stated purpose of fostering collaborative infrastructure for the additive manufacturing industry. However, several participants expressed concern that collaboration between private and university researchers may not take place due to competition issues, and that the industry as a whole might suffer. Another participant suggested that investments in additive manufacturing made by one company would challenge the rest of the industry to keep pace. The participant said that, even though a company might not share its proprietary information, it might encourage others by its progress. The same participant also identified the development of mathematical analytical and design tools, as well as training efforts, as fundamental

[21] GAO, *Science, Technology, Engineering, and Mathematics Education: Strategic Planning Needed to Better Manage Overlapping Programs across Multiple Agencies*, GAO-12-108 (Washington, D.C.: Jan. 20, 2012).

work that the government could support to move the industry forward, regardless of information sharing practices between companies. Another participant added that the federal government could encourage the purchase and use of additive manufacturing equipment with a tax subsidy, such as a bonus depreciation tax deduction.[22]

Participants Said the Government Should Monitor Areas That Could Be Affected by an Increased Use of Additive Manufacturing

Forum participants identified four key areas that could be affected by future growth in additive manufacturing: (1) national security, (2) product liability, (3) intellectual property, and (4) environmental, health, and safety concerns. These four areas were identified as being particularly challenging and perhaps different from challenges caused by other emerging technologies. Most participants agreed with the call for a “wait and see” posture with the government closely following developments in the field and ready to act when required, but no sooner.

Forum participants said that developing and maintaining an infrastructure that supports widespread use of additive manufacturing technologies may raise national security issues. Specifically, they raised the need to balance the national security benefits of a strong U.S. industrial base with the national security risks related to increased use of additive manufacturing. For example, they said hostile nations or factions could use the technology to harm the United States or its representatives abroad, and the military and intelligence communities are particularly concerned with the potential for additive manufacturing to permit the production of weapons or weapons components in ways that are less observable than with current conventional manufacturing processes and facilities. For instance, additive manufacturing could supplement the proliferation of small arms and light weapons. Because additive manufacturing has been recognized as a technology with important military applications by DOD, finding the appropriate mechanisms to avoid damaging the industry, while protecting national security, will likely be an ongoing challenge. Many participants expressed concern that

[22] Taxpayers are allowed to take an income tax deduction to cover the depreciation of certain property used in a business. A bonus depreciation allows the taxpayer to deduct more of the costs of the investment in the first year.

overly restrictive export controls or licensing requirements on additive manufacturing technologies could be an impediment to the economic growth of U.S. companies. One participant said that the rationale for restrictive export controls presupposed a U.S. monopoly on the technology, which the participant asserted was not the case. Another participant said there is a need to balance a protectionist, “Fortress America” view of national security with the benefits of positively engaging with global commerce. One participant also emphasized that the cybersecurity capabilities of a system need to be built-in and considered in the design and development of the product, including design files, materials, and machines.

Participants cited uncertainty about product liability protections when additive manufacturing technology is used by individual consumers with home 3D printing systems. A forum participant said this development could complicate traditional regulatory roles and result in insufficient legal protections for those harmed by dangerous products. There is also a challenge in regulating the safety of final products produced through additive manufacturing by small organizations and individuals. These small organizations and individuals are less likely to be aware of federal safety regulations for final products and may not have the quality assurance systems that larger organizations do. For example, individual consumers injured by a product printed with a home 3D printing system may have difficulty seeking legal recourse because strict product liability applies only to commercial sellers.[23] However, it is unlikely the individual consumer will have a commercial seller to sue for the defective product, especially if the consumer uses a 3D printer to manufacture the product at home. Therefore, it is uncertain who, if anyone, could be held liable for a defective product manufactured with a home 3D printer. One participant noted that liability law historically has adapted to new situations as they have emerged, but that policymakers should be prepared to make changes if problems arise.

Forum participants also discussed the potential risk for infringement of intellectual property rights with regard to additive manufacturing equipment, design files, and product manufacturers. They said it is

[23]Persons engaged in the business of selling or distributing products may be liable for harm to others caused by a defect in the product sold. Strict product liability holds those sellers or distributers legally responsible for the harm caused by the defective product, even if the seller did not intentionally or negligently cause the defect.

possible that an increased use of additive manufacturing and digital design files could lead to disputes between additive manufacturing users and intellectual property holders. Currently, a limited number of products can be effectively produced by additive manufacturing, particularly on the machines available at a low cost to the consumer. However, as the technology improves and proliferates, machines will likely be capable of building more complex items and will become more available to consumers. Moreover, 3D scanning technology and sharing of design files on the Internet may make it easier to infringe upon intellectual property rights. Participants noted that, while copying and counterfeiting exist in every industry, 3D scanning and additive manufacturing technologies may make such activities easier.

Finally, participants discussed whether, and to what extent, the government should regulate environmental, health, and safety (EHS) concerns when implementing and using additive manufacturing processes. One participant noted that some EHS concerns for additive manufacturing are not markedly different from conventional manufacturing techniques such as welding, but some other concerns are unknown. EHS concerns unique to additive manufacturing have not been clearly identified, but it may be that safety practices for handling materials and managing equipment could be similar for additive and conventional manufacturing. Forum participants also raised EHS concerns related to the maker community’s use of 3D printing. In a large manufacturing organization, safety assessors monitor new machines and set-ups and determine the appropriate personnel and environmental safeguards. The participants expressed some concern that novice or home users would not be able to recognize or resolve EHS concerns associated with additive manufacturing.

Participants Encouraged Government Consideration of Trade-offs for Potential Policy Actions Affecting Additive Manufacturing

Forum participants said that as the government considers policy actions to address challenges that could advance additive manufacturing, as well as the possible risks associated with an increased growth in the sector, it needs to consider the trade-offs involved in such actions. Trade-offs exist for any government action and participants encouraged government decision makers to acknowledge that there is a cost to government intervention. They suggested it would be worth waiting to see what is possible and what the real state of the art is before, as one participant put it, “running off to try to intercept a concern.” Another participant described well-exercised government control for additive manufacturing as the crafting of solutions to only those problems and concerns that can be clearly articulated.

Given the constraints on federal resources, participants questioned how deeply the federal government should be involved in promoting specific applications of additive manufacturing. For instance, as previously mentioned, while there is a lot of attention being paid to additive manufacturing, participants said that additive manufacturing will not replace conventional manufacturing, but it will be an additional tool for manufacturing parts to be used, when appropriate, from a cost-benefit perspective. Further, forum participants discussed whether additive manufacturing-specific training should come from government efforts, or from industry, and to what degree additive manufacturing technical details might be taught on-the-job to a workforce with sufficient training in design. Concerning market support, participants discussed whether or how the government should take steps to subsidize the early stages of technology development or provide incentives to program managers to mitigate the real or perceived risk of taking on additive manufacturing projects. Forum participants suggested that the federal government could support new technologies through tax or other revenue policies.

Participants encouraged a national dialogue about government involvement in additive manufacturing for production of functional parts, which could include a substantive discussion of the trade-offs inherent in government involvement. Participants said that clearly articulated goals for additive manufacturing would help policymakers assess trade-offs associated with government action, and react accordingly. One forum participant noted that the development of such high-level goals must come from a consensus process, and they cannot be developed by the government alone. For example, forum participants said one goal for additive manufacturing could be enhancing the international competitiveness of the United States. Participants noted that additive manufacturing was originally developed in the United States, but the production of additive manufacturing machines and materials now is occurring in countries throughout the world, especially in Sweden, Germany, and China. One participant stated that, when a country does not control the technology and the manufacturing of the equipment itself, it becomes difficult to be a leader in the use of that equipment. Participants suggested that enhancing the ability of U.S. companies to compete in the global marketplace could be assisted by America Makes, or a similar public-private partnership. The administration has voiced support for advanced manufacturing, including the ability to quickly respond to customer needs through innovations in production processes and the supply chain. Participants suggested that the United States focus discussions on where the federal government can enable U.S. strengths and level the playing field with other nations that are making investments in additive manufacturing capabilities.

The discussion among forum participants also generated a list of possible focus areas: strategic planning and idea generation for the sector, ways to ramp up production of additive manufacturing machines, deployment of the technology, the creation of analytical or design software tools, and the development of new materials. The exact mechanisms to be used in pursuing any of these focus areas were not identified. Instead, participants emphasized the need for broad thinking to select and design the most effective initiatives. Participants said that collaboration, coordination, and communication were critical areas in which the federal government could help build the body of knowledge and take other steps that could move the technology forward.

Appendix I: Objectives, Scope, and Methodology

This report summarizes discussions from the Comptroller General Forum on Additive Manufacturing that was held on October 15 and 16, 2014. The forum focused on three questions: (1) What are the opportunities to produce functional parts using additive manufacturing? (2) What are the key challenges, if any, to using additive manufacturing to produce functional parts? and (3) What are the key considerations for any policy actions that could affect the future use of additive manufacturing to produce functional parts?

To inform our understanding of additive manufacturing and to establish the scope and agenda for the forum, we met with relevant agency officials from the National Institute of Standards and Technology, the U.S. Patent and Trademark Office, the U.S. Copyright Office, and the Consumer Product Safety Commission. We also met with key additive manufacturing stakeholders, such as the National Additive Manufacturing Innovation Institute (America Makes), the Association for Manufacturing Technology, Stratasys, and EWI.[1] We attended additive manufacturing conferences sponsored by Oak Ridge National Laboratory and by SME.[2] We also conducted a comprehensive literature review. We reviewed literature on technical and policy issues related to additive manufacturing. Articles selected for the literature search were found in one of the following three ways:

1. searches of databases through RefWorks,
2. interviews with relevant agency officials and other key informants (i.e., individuals identified as having relevant expertise or knowledge about technical and policy issues related to additive manufacturing), and
3. references in literature.

To determine whether the selected articles were relevant, we reviewed each one and excluded those that were not related to the use of additive manufacturing for the production of functional parts. For instance, we

[1]EWI was formerly known as the Edison Welding Institute.

[2]SME was formerly known as the Society of Manufacturing Engineers.

excluded articles on rapid prototyping, home-user-produced items, particular additive manufacturing printer technologies, or niche applications. We focused on broad technical and policy issues to address the researchable questions. When an article was excluded, we noted the reason for exclusion. In total, nearly 160 documents were analyzed as part of this literature review. Each of the relevant documents was reviewed by a primary and secondary analyst, and the following information was recorded, as appropriate:

1. ID – the Ref ID from the RefWorks search results;
2. title – the title of the article;
3. source – the title of the journal where the article appeared or other source of the article;
4. publication year – the year that the article was published;
5. authors/contact – the author(s) or responsible contact(s) provided in the article;
6. company/agency/industry use of additive manufacturing objects – companies, agencies, or industries identified as using additive manufacturing objects and any provided information about what objects they are using and how they are using them;
7. technical and policy challenges and opportunities identified – any technical and policy issues discussed in the article, including limitations, risks, benefits, and other important issues related to the advancement and future of additive manufacturing; and
8. other potential sources identified – any other potential sources (e.g. publications, experts, etc) that may provide information about how additive manufacturing objects are being used and technical and policy issues related to additive manufacturing.

We used the results of the literature review, as well as information obtained from interviews with experts, agency officials, and other key informants and gathered through attending relevant conferences, to identify and categorize the technological and policy issues. We also used the information to determine the various sessions that comprised the forum agenda. We prepared background materials and discussion papers that framed the issues to be discussed during each session. The identification and categorization of technological and policy issues also aided in determining the needed expertise at the forum. To identify participants for the forum, we contracted with the National Academies to assist us.[3] Overall, the participants included individuals with a range of backgrounds, experiences, and knowledge who comprised the following two main groups:

- Representatives from government and business involved with current or planned uses of additive manufacturing to produce operational parts and products who could address current and potential applications, benefits, and challenges.
- Experts who could address how the use of additive manufacturing may affect areas such as supply chain management, product safety, intellectual property protection, and national security, as well as potential changes to existing policy frameworks to address additive manufacturing challenges.

To identify experts for the forum, the National Academies staff received input and recommendations from several of its internal boards and advisory groups, including the National Materials and Manufacturing Board and its standing committee on Defense Material Manufacturing and Infrastructure; Space Studies Board; Aeronautics and Space Engineering Board; Board on Physics and Astronomy; Laboratory Assessments Board; and the Computer Science and Telecommunications Board. The staff then acquired biographical information on the suggested experts and compared their backgrounds with the topics for the forum. The National Academies staff made initial contact with potential experts to determine their interest and availability for the forum. The National Academies presented GAO a preliminary list of experts for the meeting. GAO provided feedback on the list, and the National Academies staff made revisions to the list. From the revised list, GAO selected 23 meeting attendees, which were subsequently invited by the National Academies.[4] GAO made its selections based on the candidates' biographies to ensure a suitable number of experts to cover all the necessary topics to be covered in the forum and to ensure balance and representation on a wide

[3]GAO has a standing contract with the National Academies under which the National Academies provides assistance in convening groups of experts to provide information and expertise in our engagements.

[4]Though they were initially available, two of the invited experts were unable to attend the meeting. One of the invited experts designated a replacement to attend the forum meeting.

range of viewpoints. From each of these attendees, the National Academies collected a questionnaire to identify any potential conflicts of interest, including investments and other assets, sources of earned income, organizational positions, and any other relevant circumstances.

The Comptroller General Forum on Additive Manufacturing was held at the GAO headquarters building in Washington, D.C. The forum was recorded, and the sessions were transcribed. In total, 22 experts, as well as several senior level GAO staff participated in the forum. The forum participants are listed in appendix II, and the agenda is included in appendix III. All sessions were structured as facilitated discussions.

The focus of the first day was to discuss the opportunities for additive manufacturing to produce functional parts and to identify the technical and policy challenges of using additive manufacturing in this way. At the conclusion of the first day of the forum, we compiled a list of 35 challenges that were raised during the sessions that are limiting the use of additive manufacturing for producing functional parts. This list of challenges was also informed by the information obtained in advance of the forum. At the beginning of the second day of the forum, we presented this list of challenges to the participants. To ensure the accuracy of the list, we asked the participants to indicate whether or not they agreed that we had accurately characterized the challenges, whether anything was missing, and whether any challenges could be combined. We edited the list in response to the participants' feedback. Following the review, we had the list of 37 challenges that are included in appendix IV.

To determine the participants' views on the most important challenges, we prepared a document listing all the challenges and distributed it to each participant. The participants were instructed to choose the 10 challenges they considered most important, in no particular order. The participants' selections were tabulated and presented for further discussion later in the afternoon. The original intent was to include a second round of challenge selection to narrow the list to the top three most important challenges. However, participants decided instead to group the challenges into categories they considered most important.

Following the forum, to provide a framework to present the additive manufacturing challenges in this report, we allocated specific challenges identified by forum participants into broad categories.

At the beginning of the analysis, we developed three broad categories for various challenges identified by the participants. The initial set of categories was based generally on challenges related to different stages of the additive manufacturing process (design, construction, and verification). Specifically, we developed the following questions based on those categories:

1. Challenges to envisioning use of the technology – can we design what we want to build?
2. Challenges to using the technology – can we build what we designed?
3. Challenges to verification – can we verify we built what we intended to build?

We determined the challenges most often identified as among the 10 most important challenges, and we ended with challenges that were the least often identified as among the top 10. Multiple GAO analysts were involved and any disagreements were worked through to achieve consensus. For example, the challenge “Consensus methods and test data for qualification and certification are not sufficient” was placed in Category 3 (challenges to verification) because qualification and certification relate to verifying that the product and its materials meet a set of standards or performance criteria.

We also decided many challenges were related and could potentially be classified into multiple categories. When a challenge was classified in more than one category, all relevant category numbers were listed in order from most relevant category to least relevant. For example, the challenge “Insufficiently skilled workforce and training” was actually placed in all of the categories because skilled workers will be necessary for every aspect of the technology. However, we selected Challenge 1 (challenges to envisioning use of the technology) as the first challenge because participants repeatedly emphasized the need for a new approach to thinking about design and the underlying education needs.

We determined that the forum included discussion of challenges that currently faced the additive manufacturing industry, as well as challenges that might potentially face the industry and the government as the technology continues to develop. The determination of whether a challenge was primarily a current challenge or a potential challenge became the first level of categorization. For example, the challenge “Need for appropriate design and mathematical analysis tools for additive manufacturing products” is categorized as a current challenge because this is a problem that the industry currently faces and limits its use of the technology. However, the challenge “Difficulty in regulating final additive manufacturing products when made by laypersons" is classified as a potential challenge because there are potential problems in regulating distributed manufacturing, but these problems have not actually manifested according to participants. When a challenge was classified as potential, we did not categorize it into any numbered category.

We identified another theme in our discussion of the challenges and added a fourth category labeled "Challenges related to knowledge gaps and the need for greater understanding of technology/implications." This theme came up in forum discussions and was added to our list to better capture challenges that involved uncertainty or the need for better coordination/collaboration to build a body of knowledge. These challenges tended to involve other categories as well.

Shortly after the forum, we prepared an outline of this report and distributed it to the forum participants for their comments. Nineteen of the 22 experts who participated in the forum responded to our request for comments on the outline of the report.[5] Participants provided several technical comments, but they generally agreed with the framing of the challenges. As we drafted the report, we incorporated participants' comments, as appropriate. In addition, we provided a draft of this report to the forum participants for their comments. Eighteen of the 22 experts who participated in the forum responded to our request for comments on the draft report.[6] Participants provided several technical comments, but they generally agreed that the report accurately reflects the forum discussions. We incorporated participants' comments into the final report, as appropriate.

We conducted our work from March 2014 to June 2015 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to our objectives. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations in our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

[5]Three forum participants did not respond to our request for comments on the report outline.

[6]Four forum participants did not respond to our request for comments on the draft report.

Appendix II: Forum Participants

The Honorable Joseph Benkert
Former Assistant Secretary of Defense for Global Security Affairs
Vice President
The Cohen Group

Mr. Anthony DeCarmine
Chief Technology Officer
Oxford Performance Materials

Mr. Carl Dekker
President
Met-L-Flo Inc

Dr. Phill Dickens
Professor of Manufacturing Technology
University of Nottingham

The Honorable Gene L. Dodaro
Comptroller General of the United States
U.S. Government Accountability Office

Mr. Michael Dunn
Manufacturing Technology (ManTech) Program
Department of Defense

Ms. Nora Engstrom
Professor
Stanford Law School

Dr. Slade Gardner
Fellow
Lockheed Martin Corporation

Capt. Gerald Grant
Service Chief, 3D Medical Applications Center
Director, Craniofacial Imaging Research
Walter Reed National Military Medical Center

Mr. Matthew K. Hlavin
Chief Executive Officer

Rapid Prototype and Manufacturing LLC

Mr. John Hornick
Partner
Finnegan, Henderson, Farabow, Garrett & Dunner, LLP

Mr. Kevin Jurrens
Deputy Chief, Intelligent Systems Division
National Institute of Standards and Technology

Dr. Nancy Kingsbury
Managing Director, Applied Research and Methods
U.S. Government Accountability Office

Dr. Howard A. Kuhn
Adjunct Professor
Swanson School of Engineering
University of Pittsburgh

Dr. Thomas Kurfess
Professor
HUSCO/Ramirez Distinguished Chair, Fluid Power and Motion Control
Georgia Institute of Technology

Dr. Aija Leiponen
Associate Professor
Dyson School of Applied Economics and Management
Cornell University

The Honorable Donald Manzullo
Former United States Congressman representing the 16th District of Illinois

Dr. Michael McGrath
Vice President
Analytic Services Inc.

Mr. Ed Morris
Vice President and Director
National Center for Defense Manufacturing and Machining
America Makes – The National Additive Manufacturing Innovation Institute

Dr. Susan Offutt
Chief Economist
U.S. Government Accountability Office

Mr. Neal Orringer
Vice President of Alliances and Partnerships
3D Systems

Mr. Michael Peretti
Director, Materials & Manufacturing Advanced Programs
General Electric Aviation

Dr. Timothy M. Persons
Chief Scientist
U.S. Government Accountability Office

Ms. Susan A. Poling
General Counsel
U.S. Government Accountability Office

Dr. Steve Pollack
Director, Office of Science and Engineering Laboratories
Food and Drug Administration

Ms. Michelle L. Proctor
Director of Innovation
FedEx

Mr. Michael Weinberg
Vice President
Public Knowledge

Appendix III: Forum Agenda

Comptroller General Forum on Additive Manufacturing
October 15-16, 2014
Agenda
Wednesday October 15, 2014

8:00 a.m.	**Arrivals/Check-in** Continental Breakfast	McCarl Room
8:30 a.m.	**Opening Session** *Welcome and Introductions* • The Honorable Gene L. Dodaro Comptroller General of the United States U.S. Government Accountability Office *Forum Overview* • Dr. Timothy M. Persons, Chief Scientist U.S. Government Accountability Office *Significance of Additive Manufacturing to the Congress* • The Honorable Evan Bayh, former United States Senator and former Governor of Indiana • The Honorable Donald Manzullo, former United States Congressman	Staats Briefing Room
9:15 a.m.	**Opportunities for Additive Manufacturing to Directly Produce Parts and Products**	Staats Briefing Room
11:00 a.m.	**Break**	
11:15 a.m.	**Technical Challenges of Additive Manufacturing** Working Lunch	Staats Briefing Room McCarl Room (lunch pickup)
1:30 p.m.	**Issues Affecting the Development and Adoption of Additive Manufacturing**	Staats Briefing Room
3:30 p.m.	**Break**	
3:45 p.m.	**Policy Implications Arising From Using Additive Manufacturing for Direct Part Production**	Staats Briefing Room
5:30 p.m.	**Reception**	McCarl Room

<u>Thursday, October 16, 2014</u>

8:00 a.m.	**Arrivals** Continental Breakfast	McCarl Room
8:30 a.m.	**Review of Issues Discussed on Day 1**	Staats Briefing Room
9:00 a.m.	**Importance of Addressing Additive Manufacturing Issues for Direct Part Production**	Staats Briefing Room
10:30 a.m.	**Break**	
10:45 a.m.	**Key Considerations for Government Policies to Address Additive Manufacturing Issues for Direct Part Production** Working Lunch	Staats Briefing Room McCarl Room (lunch pickup)
1:30 p.m.	**Forum Summary and Concluding Remarks**	Staats Briefing Room
2:00 p.m.	**Adjourn**	

Appendix IV: Challenges Identified by Forum Participants

Forum participants identified the following challenges, listed in no particular order, that potentially limit the use of additive manufacturing for functional part production:

- Consensus methods and test data for qualification and certification are not sufficient
- Need for improved suite of standards for additive manufacturing
- Lack of inspection and quality standards for additive manufacturing products
- Need for better process control to improve system performance and repeatability in additive manufacturing
- Need for appropriate design and mathematical analysis tools for additive manufacturing products
- Need for appropriate design and physics-based analysis tools for additive manufacturing processes
- Limited number of additive manufacturing materials
- Need to print smaller-scale and larger-scale parts
- Difficult to scale up production
- Improved part accuracy
- Improved surface finish
- Unknown materials properties including materials compatibility
- Fabrication speed too slow
- Need to make more complex or integrated parts and products and not just shapes using additive manufacturing
- Cybersecurity risks to additive manufacturing equipment and design files
- Insufficient sharing of common data on additive manufacturing process parameters, materials, materials properties, and testing
- Need for improved collaboration and coordination among researchers
- Need for more pragmatic output from university research and development

- Need for more additive manufacturing research and development infrastructure (labs, lab equipment)
- Hype and unrealistic expectations (e.g., disconnect between expectations and reality)
- Technology’s reputation may be tarnished by bad experiences or by association with criminal activity
- Insufficiently skilled workforce and training
- Uncertainty regarding where additive manufacturing is cost-effective
- Pace of technology change may result in relatively short life-cycle or obsolescence of the equipment (5-10 years)
- Effect of additive manufacturing equipment or software revisions on process qualification
- Need for funding or access to capital for additive manufacturing investments
- Need for robust supply chain for additive manufacturing materials and systems
- Lack of incentives for program managers to take on perceived or actual risk associated with additive manufacturing
- Need to identify breadth and depth of precompetitive discussions for additive manufacturing
- Potential clash between additive manufacturing and intellectual property stakeholders
- Environmental health and safety concerns when implementing and using additive manufacturing process
- Difficulty in regulating final additive manufacturing products when made by novices
- Potential safety concerns and uncertainty of product liability protections when additive manufacturing is used by novices
- Need to avoid export controls/licensing that are impediments to U.S. additive manufacturing industry growth while still protecting U.S. national security
- Need for greater consideration of U.S. industrial base and national security concerns for additive manufacturing
- Need for improved coordination among federal agencies on additive manufacturing issues

- Lack of national strategy to enhance U.S. competitiveness and engagement in the global marketplace

Appendix V: GAO Contact and Staff Acknowledgments

GAO Contact

Timothy M. Persons, (202) 512-6412 or personst@gao.gov

Staff Acknowledgments

In addition to the contact named above, Cheryl Arvidson, Ana Ivelisse Aviles, Amy Bowser, Virginia Chanley, Eric Charles, Richard Hung, Christopher Murray, Susan Offutt, Kiera Reifschneider, Maria Stattel, Andrew Stavisky, Anne Stevens, and Walter Vance made key contributions to this report.

Juanita Aiken, Pille Anvelt, Alisa Beyninson, Andrew Burton, F. Kendall Childers, Dawn Godfrey, Allison Harris, Debra Johnson, Armetha Liles, Ashley McCall, Katrina Pekar-Carpenter, Marilyn Wasleski, Angela Watson, and Alexandra Willcox also contributed to this report and the conduct of the forum meeting.

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