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Additive Manufacturing Technology: Potential Implications for U.S. Manufacturing Competitiveness

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Abstract

This article explores the development and application of additive manufacturing as well as initiatives in the United States and other countries to advance it. It also examines the technology's effect on firm and industry production activities, as well as the potential implications for U.S. manufacturing competitiveness focused in three industries. It concludes that the most significant factors affecting the potential of additive manufacturing to contribute to U.S. competitiveness are developing standards, improving the selection and affordability of materials, and increasing the accuracy and reliability of equipment and processes.

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INTRODUCTION

Additive manufacturing, or three-dimensional (3-D) printing, is receiving unprecedented attention. Additive manufacturing is a suite of emerging technologies that fabricates three-dimensional objects directly from digital models through an additive process, typically by depositing and "curing in place" successive layers of polymers, ceramics, or metals.[2] Unlike traditional manufacturing processes involving subtraction (e.g., cutting and shearing) and forming (e.g., stamping, bending, and molding), additive manufacturing joins materials together to build products. The number of articles published on this nascent industry rose from about 1,600 in 2011 to 16,000 in 2012.[3] The additive manufacturing market, consisting of all additively manufactured products and services worldwide, shows equally impressive growth: it rose from $1.7 billion in 2011 to $2.2 billion in 2012, by 28.6 percent.[4] Evolving and fluid, additive manufacturing technology is shaping the future of product development and manufacturing.

This article addresses three questions about additive manufacturing. First, how is this rapidly evolving technology being applied? Second, will its growth prompt changes in firm and industry production activities? Third, what are the potential implications for U.S. competitiveness in manufacturing processes and the economy? The article draws on the experiences of three industries that are thus far among the top users of additive manufacturing: automotive, medical, and aerospace.[5] It examines how additive manufacturing is used in these industries. The article also reviews the dynamics that affect wider deployment of additive manufacturing, such as technological challenges, new innovations, and industry and government initiatives to facilitate its use. It concludes that the most significant factors affecting the potential of additive manufacturing to contribute to U.S. competitiveness are developing standards, improving the selection and affordability of input materials, and increasing the accuracy and reliability of equipment and processes.[6]

Originally conceived as a way to make prototypes,[7] additive manufacturing has improved to the extent that it is increasingly used to deliver final products.[8] Recent improvements include enhancements of the speed and performance of additive manufacturing machinery, an expanding range of input materials, and falling prices for both machinery and materials. These

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[2] USDOE, "Advanced Manufacturing: Pursuing the Promises," August 2012, 1.

[3] Wohlers, "Additive Manufacturing," June 2013, 67–73.

[4] Park, "Unsurprisingly, Wohlers," May 24, 2013, 1.

[5] For the purposes of this article, "automotive" is used interchangeably with "motor vehicle," and "medical" encompasses "dental."

[6] Sealy, "Additive Manufacturing as a Disruptive Technology," 2012, 92.

[7] Rapid prototyping and additive manufacturing differ according to product characteristics. While prototypes are used to show special product properties or functions during the product development phase, additive manufacturing also delivers final products.

[8] Approximately 28 percent of additively manufactured parts are final products. Wohlers, "Additive Manufacturing," June 2013, 7–12. Desktop computers and industrial lasers have facilitated advancements in additive manufacturing.

advancements are likely to inspire further adoption of additive manufacturing in the United States and around the world in coming years.

Additive manufacturing provides an important opportunity to advance the U.S. manufacturing industry, which has the largest research and development (R&D) expenditure for manufacturing overall of any country.[9] Though barriers to production with the technology exist, unique capabilities make additive manufacturing processes superior to conventional manufacturing for some products. These capabilities include constructing previously impossible geometries, such as pyramidal lattice truss structures with hollow trusses,[10] and significantly reducing material waste by building layer by layer and using only the material necessary.[11] Firms that employ additive manufacturing are beginning to achieve benefits such as increasing supply chain efficiencies; reducing time to market; moving from mass production to mass customization; and sustaining the environment.[12] As a result, the technology is receiving attention in policy as well as manufacturing circles. President Obama extolled additive manufacturing in his 2012 State of the Union address, stating it could "revolutionize the way we make almost everything."[13]

OVERVIEW OF TECHNOLOGY

Process

Additive manufacturing begins with computer-aided design (CAD) modeling software that takes a series of digital images of a design or object and sends descriptions of them to a professional-grade industrial machine. The machine uses the descriptions as blueprints to create the item by adding material layer-upon-layer. Layers, which are measured in microns, are added by the hundreds or thousands until a three-dimensional object emerges. Raw materials may be in the form of a liquid, powder, or sheet and are typically plastics and other polymers,[14] metals, or ceramics.

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[9] OECD, Structural Analysis Database (accessed September 24, 2013).

[10] Queheillalt and Wadley, "Pyramidal Lattice Truss Structures," 2005, 132–37; A truss that resembles latticework because of diagonal placement of members connecting the upper and lower chords.

[11] Subtractive manufacturing processes such as machining take raw material and remove and shape it into the desired final form. In some cases, over 90 percent of a billet of raw material may be removed before the product is finished. Campbell and Slotwinski, "Metrology for Additive Manufacturing," 2013, 154.

[12] Matthews International Corporation representative, interview by author, March 5, 2014.

[13] White House, "State of the Union Address," January 24, 2012.

[14] A polymer is a chemical compound made of small molecules that are arranged in a simple repeating structure to form a larger molecule. Merriam-Webster Dictionary website, *http://www.merriam-webster.com/dictionary/polymer* (accessed May 21, 2014). Examples of polymers often used in additive manufacturing are polycarbonate and high-density polyethylene.

The numerous additive manufacturing processes differ according to the materials and methods of patterning and fusing layers they employ. Major processes include material extrusion,[15] material jetting,[16] binder jetting,[17] sheet lamination[18] vat photopolymerization,[19] powder bed fusion,[20] and directed energy deposition.[21] Some of these melt or soften material to produce the layers, while others cure liquid materials using different sophisticated technologies.[22] An image of selective laser sintering, an additive manufacturing process that is a type of powder bed fusion, appears below (box 1) as an example.

Thirty-one manufacturers from around the world produced professional-grade industrial additive manufacturing machines in 2011, compared to 32 in 2010 and 35 in 2009. In 2010 and 2011, 9 of these companies sold more than 100 machines each. Firms that produce additive manufacturing machines range from those that produce and sell fewer than 10 per year, to those that sell hundreds of machines per year.[23]

The United States leads in the production and sales of professional-grade industrial additive manufacturing machines, with 35,753 units sold between 1998 and 2011. Israel and Germany made 4,556 and 3,980 units, respectively, during the same period. Powder bed fusion and binder jetting are the most common processes used by leading vendors, more of whom (70 percent) use metal than any other material.[24] Table 1 presents several leading vendors that manufacture machines, an overview of processes and applications, and the most frequently used materials for each process.

[15] Material extrusion is the selective dispensation of material through a nozzle or orifice. Wohlers, *Wohlers Report 2012*, 2012, 68.

[16] Material jetting is the selective deposition of droplets of build material via ink-jet print head nozzles. Wohlers, *Wohlers Report 2012*, 2012, 68.

[17] Binder jetting is the selective deposition of a liquid bonding agent through ink-jet print head nozzles to join powder materials. Wohlers, *Wohlers Report 2012*, 2012, 68.

[18] Sheet lamination involves bonding sheets of material together. Wohlers, *Wohlers Report 2012*, 68.

[19] Vat photopolymerization is selective curing of liquid photopolymer (light-sensitive polymer) in a vat via light-activated polymerization. Wohlers, *Wohlers Report 2012*, 2012, 68.

[20] Powder bed fusion is selective fusing of powder bed regions via thermal energy. Wohlers, *Wohlers Report 2012*, 2012, 68.

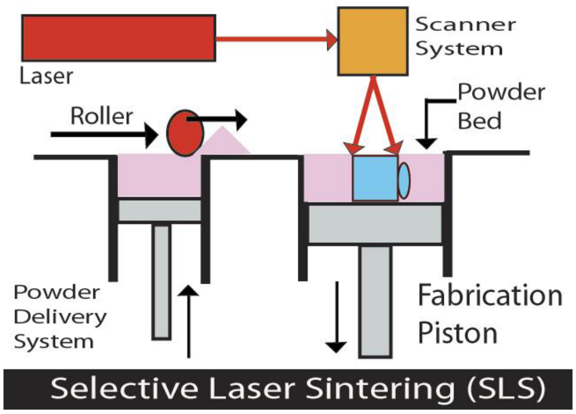
[21] Directed energy deposition is simultaneous fusion and deposition of material. Wohlers, *Wohlers Report 2012*, 2012, 68.

[22] A list of process category names and definitions which the ASTM International Committee F42 on Additive Manufacturing Technologies approved in January 2012 appears in the appendix; Additive manufacturing machines range in size from desktop models, which weigh just a few pounds, to an Objet-Stratysys model, which measures 9 feet x 6.7 feet x 5.5 feet and weighs 6,325 pounds.

[23] Wohlers, *Wohlers Report 2012*, 2012, 83.

[24] Wohlers, *Wohlers Report 2012*, 2012, 74, 82.

BOX 1 Selective Laser Sintering: an Additive Manufacturing Process



Source: Martello Co., http://www.martello.co.uk/rapid_prototyping.htm (accessed August 3, 2013).

Selective laser sintering uses a high-powered pulse laser to fuse particles of plastic, metal, or glass powders into a desired three-dimensional shape. The laser selectively fuses powdered material by scanning cross sections generated from a 3-D digital description of the design or object. After each cross section is scanned, the powder bed is lowered by one layer of thickness, and a new layer of material is applied. The process is repeated until the object is complete.

TABLE 1 Leading industrial additive manufacturing machine vendors, 1988-2011

Vendors/Production Sites	**Processes/Applications**	**Materials**
3D Systemsa (US, AUS, NED, ITA)	Binder jetting, material jetting, vat photopolymerization, powder bed fusion	Plastic, polymer, metal
Beijing Tiertime (CH)	Material extrusion	Polymer
DWS (ITA)	Vat photopolymerization	Polymer
Envisiontec (GER, US)	Vat photopolymerization , material extrusion	Biomaterial, ceramic, polymer
EOS (GER)	Powder bed fusion	Ceramic, metal, polymer
ExOnea (US, GER, JPN)	Binder jetting	Ceramic, polymer, metal
Objetb (ISR, US, GER, Asia)	Material jetting	Biomaterial, polymer
Solidscape (US)	Material jetting	Plastic
Stratasys[a, b] (US, GER, IND)	Material extrusion	Polymer
Z Corp. (US)	Powder bed fusion	Plastic, metal

Sources: Wohlers, *Wohlers Report 2012*, 2012, 135, 136; “Introduction to Additive Manufacturing,” Ceramic Industry, December 2012.

[a] Stratysys acquired Solidscape in 2011, and merged with Objet in 2012; 3D Systems acquired Z Corp. in 2012.

[b] Also fabricates parts.

Additive manufacturing offers industry a range of unique possibilities. The technology makes it possible, for example, to produce viable three-dimensional objects of virtually any complex geometry without significantly increasing the cost of the parts.[25] Additive manufacturing also has the potential to transform the rules of design by reducing—and perhaps even eliminating—the constraints of molds and dies.[26] Major industrial sectors additively manufacture parts ranging from visual aids to patterns for metal casting. Due to the speed and efficiency with which additive manufacturing can produce prototypes and parts,[27] the technology will have the greatest impact on products that require high customization, have complex designs, and are made in small quantities.[28]

However, additive manufacturing is not yet suitable for mass production. Inherent limitations in the processes include lengthy build time: for example, additive manufacturing processes are capable of creating a 1.5 inch cube per hour, on average, while an injection molding machine can produce several similar parts in under a minute. Current additive manufacturing technologies are unlikely to be able to create parts as quickly as molding technologies.[29] Other limitations include the size of the objects that can be made, and the cost and size of the machines and materials used.[30]

U.S. Additive Manufacturing Market and Major Industrial Sectors

The United States has several advantages in manufacturing in general, and in additive manufacturing in particular. For example, U.S. R&D spending for total manufacturing in 2011 was $415.0 billion, the highest among the countries for which Structural Analysis (STAN) data from the Organisation for Economic Co-operation and Development are available.[31] Additionally, the technology was predominantly developed in the United States, where several leading producers of additive manufacturing machines, including Stratasys and 3D Systems, are based. In 2011, the United States accounted for 38.3 percent of the cumulative installed industrial

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25 Georgia Institute of Technology Representative, interview by author, June 25, 2013.

26 Wohlers, *Wohlers Report 2012*, 2012, 183. When machine tooling is not needed and the restrictions of design for manufacture and assembly are eliminated, the possibilities for design are limited only by the available tools and a designer's imagination.

27 Vacari, "3D Printing Industry," April 19, 2013, 3.

28 In traditional manufacturing, the prototype, tooling, and setup processes are too time-consuming and expensive to profitably produce small volumes.

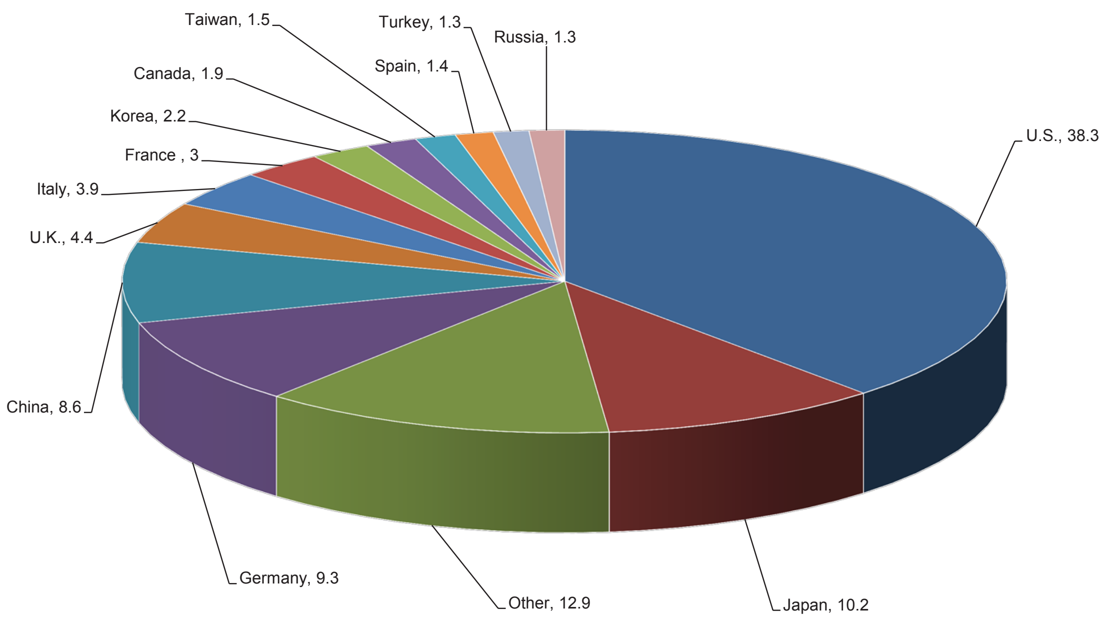
29 Campbell et al., "Could 3D Printing Change the World?," October 2011, 6. If production is decentralized, then hundreds of thousands of units of a product may be produced at multiple locations that are near the source of demand, rather than at one location.

30 Plastic materials for additive manufacturing can be 10 to 50 times as expensive as plastic materials for injection molding.

31 OECD, Structural Analysis Database (accessed September 24, 2013).

additive manufacturing systems (figure 1).[32] The same year, the United States accounted for 64 percent of all industrial additive manufacturing systems sold worldwide.[33]

FIGURE 1 Cumulative additive manufacturing machines, installed by country, 1988-2011, (percent of global total)



Source: Wohlers, *Wohlers Report 2012*, 2012, 20.

Leading sectors in this field, based on revenue for all additive manufacturing products and services in 2011,[34] include automotive (19.5 percent), medical (15.1 percent), and aerospace (12.1 percent) (figure 2).[35]

Information to show how broadly additive manufacturing is being deployed in the U.S. manufacturing base, and, in what specific sectors, is not yet available. However, data from the U.S. Department of Commerce show that goods using additive manufacturing methods represent less than a fraction of 1 percent of their relevant industry subsectors, implying abundant potential for growth (table 2).[36]

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[32] Wohlers, *Wohlers Report 2012*, 2012, 133.

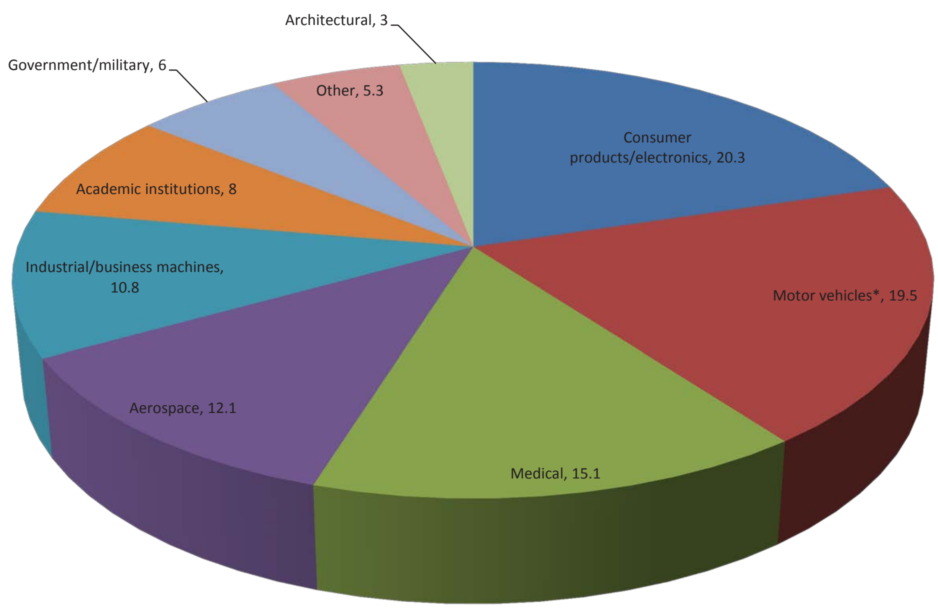
[33] Other countries with significant stocks of industrial additive manufacturing machines include Japan (10.2 percent of global total), Germany (9.3 percent), and China (8.6 percent). Wohlers, *Wohlers Report 2012*, 2012, 18.

[34] This paper focuses on the second-, third-, and fourth-largest sectors because they are relatively distinct. It does not address the single largest sector, consumer products and electronics, because it is too varied and diffuse to discuss comparably. Approximately 20.3 percent of additive manufacturing is within consumer products and electronics. Wohlers, *Wohlers Report 2012*, 2012, 18.

[35] Wohlers, *Wohlers Report 2012*, 2012, 18.

[36] Thomas, *Economics of the U.S. Additive Manufacturing Industry* (prepublication draft), June 2013, 38.

FIGURE 2 Industries served and approximate revenues (by percent) for additive manufacturing, 2011



Source: Wohlers, *Wohlers Report 2012*, 2012, 20.

Automotive

The automotive industry has used additive manufacturing to make tool prototypes and small custom parts with short production runs (in the hundreds) for decades. It is increasingly applying the technology to metals, with a focus on aluminum alloys, to construct lightweight vehicles. Additive manufacturing shipments for the U.S. automotive industry were valued at $48 billion in 2011. As noted earlier, approximately 19.5 percent of additive manufacturing occurs within the automotive industry, with additive manufacturing shipments estimated to be less than 0.05 percent of total U.S. automotive shipments.[37]

An example of an early adopter within the industry is Ford Motor Company, which has been using the technology to develop prototype parts for test vehicles since the 1980s. With industrial-grade machines that cost as much as $1 million each, Ford engineers have produced prototypes of cylinder heads, brake rotors, and rear axles in less time than traditional manufacturing would require. The company reports that use of the technology saves, on average, one month of production time when creating a casting for a prototype of a complex cylinder engine head that includes multiple ports, ducts, passages, and valves to manage fuel and air flow.[38]

[37] Thomas, *Economics of the U.S. Additive Manufacturing Industry* (prepublication draft) June 2013.

[38] Boulton, "Barbie, Auto Parts Hot Off the Press," June 6, 2013, B5.

TABLE 2 U.S. Additive manufacturing (AM) shipments, 2011

Category	Relevant industry NAICS codes	Shipments of US-made AM products (billion $)[a]	Total industry shipments (billion $)	AM share of total industry shipments (percent)[b]
Motor vehicles	3361, 3362, 3363	0.048	445.3	0.01
Aerospace	336411, 336412, 336413	0.030	157.7	0.02
Industrial/business machines	333	0.027	365.7	0.01
Medical/dental	3391	0.037	89.5	0.04
Government/military	336414, 336415, 336419, 336992	0.015	32.8	0.05
Architectural	3323	0.074	72.2	0.01
Consumer products/ electronics, academic institutions, and other	All others within NAICS	0.083	895.7	0.01
Total	332 through 339	$.25	$2,058.9	0.01

Source: Thomas, Economics of the U.S. Additive Manufacturing Industry (prepublication draft), June 2013.

[a] These values are calculated assuming that the percent of total additive manufacturing made products for each industry is the same for the U.S. as it is globally. It is also assumes that the U.S. share of AM systems sold is equal to the share of revenue for AM products.

[b] If rounded to "1" right of decimal.

Note: Numbers may not add up to total due to rounding.

*Note: For the purposes of this article, motor vehicles and automotive are used interchangeably.

**Note: The primary additive manufacturing market consists of all products and services directly associated with additive manufacturing processes, worldwide.

Additive manufacturing for automotive parts is also showing increasing potential. For instance, Daimler AG recently funded the development of the X Line 1000R System, a laser fusing machine with a large build volume[39] that uses powdered metals to additively manufacture components for vehicles and engines. The machine, which was introduced at the Euromold Trade Show in November 2012, has a build chamber of 23.6 inches x 15.7 inches x 19.7 inches and a layer thickness of 20 to 100 microns. The new machine has a high-powered laser in the kilowatt range, enabling as much as 10 times more productivity than standard laser fusing machines used in additive manufacturing.[40]

Automotive companies are applying additive manufacturing to an expanding range of parts, including engines and vehicle bodies. An extreme example is KOR EcoLogic's Urbee, 60 percent of which will be additively manufactured. The frame, chassis and engine will be conventionally manufactured from metal.[41] In March 2013, KOR EcoLogic announced that it is collaborating

[39] Build volume refers to the external dimensions.

[40] Brooks, "Auto Giant Harnesses New Super-scale Laser," November 15, 2012, 7.

[41] Sharma, Ananya, "Interaction with Jim Kor," January 24, 2014.

with Stratasys, Ltd., a maker of additive manufacturing equipment, to produce the Urbee 2, a road-ready, fuel-efficient car.[42] The two-passenger vehicle will be able to travel 70 miles per hour on the freeway, and use a biofuel such as ethanol.[43]

When additive manufacturing can produce larger components, the automotive industry will likely adopt the technology more broadly. Like the aerospace industry, as discussed later, the automotive industry has high demands for performance and weight reduction that additive manufacturing can help to address.

Medical

The medical industry is another leading user of additive manufacturing. Additive manufacturing is being used to create customized medical devices that closely replicate the human form. Approximately 15.1 percent of U.S. additive manufacturing takes place within this industry, with additive manufacturing shipments estimated to be $37.2 million—again, less than 0.05 percent—of medical and dental manufacturing.[44] It is the dominant technology for manufacturing customized in-the-ear hearing aids, which have dramatically increased patient comfort. Additive manufacturing has also been used worldwide to create approximately 30,000 prosthetic limbs, more than half a million dental implants, and countless other devices.[45] Shipments for U.S. manufacturing of medical and dental products amounted to $89.5 billion in 2011.[46]

One of the most well-known applications of additive manufacturing is InvisAlign orthodontics. Align Technology, Inc. uses stereolithography, a form of vat polymerization, to custom-make a series of clear plastic aligners that correct malocclusions[47] and straighten teeth without the use of metal or ceramic braces and wires. Patients wear sequential liners, which they change about every two weeks, until treatment is complete. In 2012, Align Technology shipped 363,540 cases of aligners and, as of March 2013, had trained more than 78,000 dentists and orthodontists worldwide to use the technology to fabricate products on-site.[48]

In recent years, scientists have devised a means of using a patient's cells to additively manufacture skin tissue and an array of other human body parts. In February 2013, doctors at Weill Cornell Medical College and biomedical engineers at Cornell University announced that they had used additive manufacturing and injectable gels made of live cells to build a facsimile of a human ear.[49] According to one industry expert, "the ability to manufacture living human tissue for medical research and clinical practice has the potential to reshape the future of medicine."[50]

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[42] Owano, "Kor Ecologic," February 28, 2013, 1.

[43] Owano, "Kor Ecologic," February 28, 2013, 1.

[44] Wohlers, *Wohlers Report 2012*, 2012, 18.

[45] Campbell, Bourell, and Gibson, "Additive Manufacturing," 2012, 258.

[46] Thomas, *Economics of the U.S. Additive Manufacturing Industry* (prepublication draft), June 2013.

[47] A malocclusion is a misalignment of teeth or incorrect relation between the teeth of the two dental arches.

[48] MarketWired, "Align Technology Announces," April 18, 2013, 1.

[49] Prototype Today, "3D Printer Creates Ear Using Injectable Gels," February 28, 2013.

[50] Keith Murphy Selko, CEO at Organovo, *IndustryWeek*, "The Next Wave of Manufacturing," June 6, 2013, 3.

The pharmaceutical industry is also applying the technology. For example, additively fabricating a single custom-made daily pill for each patient eliminates the need to keep track of multiple medications. Identification markings on the pill can eliminate the confusion and uncertainty of conventional medicines.[51]

While there are no formal projections of future use, experts anticipate new machines and new processes will expand applications, particularly in orthopedic implants.[52]

Aerospace

Additive manufacturing holds significant potential for the aerospace industry, which requires parts that are lightweight, strong, and geometrically complex—and typically produced in small quantities. Total (both traditional and additive) manufacturing shipments in the U.S. aerospace industry were estimated at $157.7 billion in 2011. Aerospace accounts for approximately 12.1 percent of additive manufacturing, with the total shipments estimated to be $29.8 million, or less than 0.05 percent of the U.S. aerospace industry.[53]

Aerospace firms are increasingly turning to the technology to reduce the costs of developing models and prototypes and of creating components. In a constant effort to reduce aircraft weight,[54] the industry is developing a growing proportion of its parts from titanium, plastic, and other lightweight materials. Many of these materials are costly, and additive manufacturing can make it possible to keep the amount used to a minimum. Aircraft landing gear, for example, can be additively manufactured from titanium layer by layer—rather than cut from a titanium block—thereby greatly reducing material waste and costs.[55] In addition, additive manufacturing uses these materials to create parts in geometries that may not be possible with conventional manufacturing. It can also significantly reduce the waste generated in producing the materials themselves, as well as in manufacturing and using the components.[56]

The increasing breadth and sophistication of these applications are, in turn, driving needs for improvements in process control, materials, and inspection to ensure safety.[57] Boeing, Inc., for example, has additively manufactured more than 200 different parts for 10 aircraft platforms.[58] Boeing has also used roughly 20,000 additively manufactured parts in military and commercial

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51 Lipson, "Frontiers in Additive Manufacturing," Spring 2012, 1.

52 BoneZone, "The Future of Additive Manufacturing," March 5, 2013.

53 Wohlers, *Wohlers Report 2012*, 2012, 18.

54 Rucks, "What Automakers Can Learn from Boeing's Culture," March 28, 2012.

55 Lyons, "Additive Manufacturing in Aerospace," September 19, 2011, 2; Campbell et al., "Could 3DPrinting Change the World?," October 2011, 1; Campbell and Slotwinski, "Metrology for Additive Manufacturing," 2013, 154. Traditional manufacturing and subassembly of 16 parts, plus glue, of an air duct for an F-18 fighter jet is additively manufactured into a component. It is also optimized for air flow efficiencies.

56 A reduction of one kilogram in the weight of an airliner saves about $3,000 annually in fuel and reduces carbon emissions. Additive manufacturing could help build greener aircraft—especially if all of the 1,000 or so titanium parts in an aircraft could be printed. *Economist*, "3D Printing," February 14, 2011, 19.

57 Lyons, "Additive Manufacturing in Aerospace," September 19, 2011, 9.

58 Boeing.com, "Boeing Launches New Manufacturing Venture," September 3, 2002.

aircraft, including 32 different components for its 787 Dreamliner planes.[59] General Electric, the world's largest supplier of jet engines, is preparing to additively manufacture a fuel nozzle for use in thousands of jet engines.[60] These nozzles are 25 percent lighter and as much as five times more durable than the existing model, which is welded from 20 different parts.[61] General Electric reports that it may additively manufacture up to half of the parts in its energy turbines and aircraft engines in 10 years.[62]

Aurora Flight Sciences, in partnership with Stratasys, Ltd., fabricated and flew a 62-inch wing-span aircraft with a wing composed entirely of additive manufactured components. The wing was designed by Aurora and manufactured by Stratasys utilizing fused deposition modeling 3D printers.[63] Aurora anticipates additively manufacturing small, unmanned aerial vehicles—both military and civilian—in five years.[64] In a public-private venture, the National Air and Space Administration (NASA) and Pratt & Whitney Rocketdyne (PWR) jointly produced an additively manufactured rocket engine injector. A rocket engine injector is one of the most critical and expensive engine components in a launch vehicle, and typically takes up to a year to conventionally manufacture. The NASA-PWR team was able to additively manufacture it in four months while reducing costs by 70 percent.[65]

Despite these advances, limits on the size of goods produced by additive manufacturing have likely constrained adoption of this technology in the aerospace industry. Issues with materials, accuracy, surface finish, and certification standards have further limited its use.[66]

Beyond these aerospace/medical/automotive uses, additive manufacturing has applications in many other industries, ranging in size from miniature instrumentation to large structures such as the earth boring drills used in oil exploration. The applications are so broad that they cannot be easily classified, but several are seen on a recurring basis, such as specialized manufacturing fixtures and tools, power generation equipment, robotics, heat exchangers, and thermal controls.[67]

The Potential Benefits of Additive Manufacturing

Additive manufacturing competitively produces low-volume, customized, and intricate goods because it enables inexpensive design of prototypes and parts. Additional levels of product complexity do not add costs to production beyond the design stage, because once the design is set, complex layering is no more expensive than if you were to layer a cube or a sphere.

[59] Freedman, "Layer by Layer," December 19, 2011.
[60] LaMonica, "10 Breakthrough Technologies 2013," April 23, 2013, 2.
[61] Davidson, "3-D Printing Could Remake U.S. Manufacturing," June 10, 2013, 3.
[62] Davidson, "3-D Printing Could Remake U.S. Manufacturing," June 10, 2013, 3.
[63] Industry representative, interview by author, July 15, 2013.
[64] Industry representative, interview by author, July 15, 2013.
[65] Engineering.com, "3D Printed Rocket Blasts Off," July 15, 2013.
[66] Industry representative, interview by author, July 11, 2013.
[67] Castle Island, "Additive Manufacturing: What RP Will Be," n.d. (accessed May 1, 2014).

In traditional manufacturing, by contrast, the prototype, tooling, and setup processes can be too time-consuming and expensive to profitably produce small volumes. In addition to these advances, additive manufacturing technology is fostering innovation and transforming how some companies produce and deliver goods and services. Firms are beginning to employ additive manufacturing as a tool to achieve objectives such as increasing supply chain efficiencies; reducing time to market; moving from mass production to mass customization; and sustaining the environment.

Supply Chain Efficiencies

Additive manufacturing has the potential to reduce the costs of storing, moving, and distributing raw materials, mid-process parts, and end-usable parts. The ability to produce parts on demand without the need for tooling and setup could become a basis for new solutions in supply chain management. Ed Morris, director of America Makes, the federally-funded initiative set up to define and promote the future of the industry, reports that "you don't have to have the finished product stacked on shelves or stacked in warehouses anymore. . . . Whenever you need a product, you just make it. And that collapses the supply chain down to its simplest parts, adding new efficiencies to the system."[68] As noted, General Electric is now additively manufacturing hollow fuel nozzles for aircraft that it previously manufactured in pieces and assembled later. The company has thus reduced the product's supply chain.

Reducing Time to Market

Time to market is expected to shrink in additive manufacturing applications due to shorter design and prototyping cycles, more predictable factory loads, and the elimination of tooling and factory setup times for new products. The freedom to design and redesign prototypes and parts without slowing down or adding to production costs enables a more fluid product development process. Similarly, the ability of machines to read CAD files improves planning: machines know the time and material requirements necessary to build a part before it is on the machine, and can track and measure volume and capacity at any moment.[69] For example, General Motors used additive manufacturing to significantly redesign models for the 2014 Chevrolet Malibu at a much lower cost than for its previous clay sculpting processes.[70] The company reports the technology was particularly useful for updates to the new Malibu's floor console, which features a pair of integrated smartphone holders for driver and passenger. The redesigned console also weighs less, which contributes to the car's improved fuel efficiency.[71]

Mass Customization

Additive manufacturing's ability to employ multiple designs on the same machine could enable the manufacturing industry to move from mass production in factories to mass customization

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[68] Hessman, "3D Printing the Supply Chain," July 15, 2013, 2.

[69] Wohlers, *Wohlers Report 2012*, 2012, 13.

[70] Brooke, "Chevrolet Uses Rapid Prototyping," June 11, 2013.

[71] Brooke, "Chevrolet Uses Rapid Prototyping," June 11, 2013.

with distributed manufacturing.[72] Using materials ranging from plastic to titanium to human cells, additive manufacturing creates intricate products of a near-infinite variety that can be made to exact customer specifications.

Bespoke Products, a division of 3D Systems, additively manufactures custom-designed prosthetic human body parts, such as legs. The company builds models of complete legs that have sophisticated features such as body symmetry, locking knees, and flexing ankles. During the development process, customers select from a range of options for customizing their product. The additively manufactured legs cost $5,000 to $6,000 each, and have features that are not available in existing prosthetic legs, which can cost up to $60,000.[73]

Environmental Sustainability

Additive manufacturing could become a multifaceted tool for mitigating environmental impact by replacing many of the casting, molding, and other manufacturing processes that consume significant amounts of energy and produce hazardous industrial waste. The technology also imposes few constraints on product design, enabling previously separate parts to be consolidated into a single object with increased functionality while reducing the amount of energy and natural resources required to operate it. The U.S. Department of Energy reports that energy savings of 50 percent or more can be realized in applications where additive manufacturing is competitive.[74]

PRESENT TRENDS

Numerous, multifaceted dynamics are shaping additive manufacturing. As users demand more from the technology, developers are investing in increasingly advanced processes and materials. Indeed, many industry experts see additive manufacturing as a way of providing high-value, high-margin parts and products that has a potential for explosive growth. Others, however, point to weaknesses in the technology that they argue will continue to challenge development and adoption of additive manufacturing for the foreseeable future.

Drivers to Development and Adoption

A mix of market forces and technologies are driving development and adoption of additive manufacturing. Three of the most significant ones are mass customization, new and improved processes and products, and government initiatives.

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72 Distributed manufacturing, also known as distributed production and local manufacturing, is a coordinated networkof geographically dispersed manufacturing facilities.

73 Sorrell, "Bespoke Innovations Makes Beautiful, Custom Prosthetic Legs," December 22, 2010, 1.

74 USDOE, "Additive Manufacturing: Pursuing the Promises," August 2012, 2.

Mass Customization

Mass customization is a significant driver—as well as a result—of additive manufacturing.[75] In response to increasingly fragmented markets that value individualization, manufacturers across industries are using innovative manufacturing techniques and technology to both mass-produce and individually customize products.[76] In the automotive industry, additive manufacturing enables companies to quickly and distinctively design cars, and rapidly customize them. Ford Motor Company allows its customers to "build" certain aspects of a vehicle by choosing from a palette of online additively manufactured options, such as body side cladding.[77] BMW North America also provides the option to customize several of its vehicles.[78] Customers can choose from a wide variety of additively manufactured features, including trims and inlays.

The medical device industry is similarly using the technology to build customized implants and devices. The Walter Reed National Military Medical Center uses the technology to produce customized cranial plates and cutting guides for bone grafts that are less expensive than existing alternatives and better matched to the patient.[79] Additionally, 95 percent of the world's custom "in the ear" hearing aids are additively manufactured.[80]

Additive manufacturing offers numerous advantages for mass customization. Flexibility, speed, and the ability to build objects directly make it an attractive alternative to conventional machining, forging, molding, and casting of customized parts. However, business models are only now catching up with the movement toward greater mass customization. Companies are still determining how to capture individual or group customer requirements, how much input customers will have in the design process, and which parts of the product will add the most value to the customer when customized. Given the trend, the reciprocal relationship between additive manufacturing and mass customization will likely accelerate.[81]

New and Improved Processes and Products

As noted, advances are occurring in basic areas, such as manufacturing machines, and in more applied areas, such as nanotechnology.[82] Below are several of the most significant developments in additive manufacturing processes and the end products they create, as identified by the Institute for Defense Analysis.

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[75] IBISWorld, *3D Printer Manufacturing Market Research Report*, December 2012, 23.

[76] The Manufacturer, "Additive Manufacturing," January 2012, 7.

[77] Industry representative, interview by author, July 11, 2013. Body side cladding is a protective composite paneling that covers the lower part of the doors and fenders around the wheels.

[78] BMW North America website, "Build your Own," *http://www.bmwusa.com/* (accessed July 8, 2013).

[79] Scott et al., "Additive Manufacturing," March 2012, 10.

[80] Glass, "Pitch Perfect: The Quest to Create," November 9, 2012; Maxey, "3D Printing for the Hearing Impaired," January 4, 2013.

[81] Wohlers, *Wohlers Report 2012*, 2012, 187.

[82] Campbell and Ivanova, "3D Printing for the Hearing Impaired" August 2013, 8, 119-120.

Incorporating Energy and Electronics

Advances are being made in additively manufacturing conformal electronics.[83] Robotic dispensing systems could apply conformal coating to printed circuit boards to protect them against moisture, dust, chemicals, and extreme temperatures. The systems would be able to create a repeatable coating thickness and a precise coverage area that provides superior quality and reduces costs. While no commercially available additive manufacturing process currently produces conformal electronics, the concept has been demonstrated in a joint project between Sandia National Laboratory and the University of Texas at El Paso.[84] In addition, researchers at Cornell University have additively manufactured parts that embed electronics, such as conductors and zinc batteries.[85]

Creating New Structures

Additive manufacturing enables the creation of structures with distinct advantages over traditionally manufactured ones: they are more complex, have greater geometric freedom, and are more capable of performing multiple functions. The technology allows for characteristics such as nonlinear holes and re-entrant features on complex parts with little—if any—addition to cost.[86] It also enables structures, such as honeycombs and lattices for the interiors of parts, which have significant benefits: maintaining the requisite strength and stiffness while being considerably lighter than conventionally manufactured counterparts. Researchers at the Lawrence Livermore National Laboratory of the U.S. Department of Energy are additively manufacturing combinations of materials in new ways and creating materials with properties not found in nature that will further innovation and design capabilities.[87]

Three-Dimensional Scanning

New three-dimensional scanners and processing software options are expanding opportunities for designing and additively manufacturing prototypes and parts. New algorithms, for example, are able to transform relatively crude scans into quality three-dimensional surface mapping.[88] These developments hold great potential for fields such as robotics and human-computer interaction.[89]

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[83] In conformal electronics, protective material is applied to electronic circuitry.

[84] De Beer, "Additive Manufacturing: Turning Mind into Matter," May 31, 2013, 17.

[85] Scott et al., "Additive Manufacturing," March 2012, 8.

[86] Federation of European Screen Printers Associations, "3D Printing, Additive Manufacturing and Drivers for Adoption," October 2012, 9.

[87] Lawrence Livermore National Laboratory, "Additive Manufacturing: 3D Printing Metal Parts and Novel Materials," n.d. (accessed December 3, 2013).

[88] Scott et al., "Additive Manufacturing," March 2012, 10.

[89] Newcombe, "KinectFusion: Real-Time Dense Surface Mapping and Tracking," March 2011, 9.

Bioprinting

Advances in custom medical implants and devices are driving demand for additive manufacturing. As discussed, the Walter Reed National Military Medical Center has successfully produced and implanted porous cranial plates and cutting guides for bone grafts that are less expensive than existing alternatives and better matched with the patient.[90] Progress has also been made in additively manufacturing soft tissue and organs such as kidneys.[91] Heart valves and small veins have also been made, but are not yet ready for implementation.[92]

Government Initiatives and Public-Private Partnerships

As part of an effort to strengthen productivity and competitiveness in manufacturing, national governments around the world have launched several initiatives to promote additive manufacturing. China, Singapore, and Germany are investing heavily in the technology (box 2). The White House Office of Science and Technology has formed an interagency working group, and numerous federal organizations, such as the Department of Commerce, the National Science Foundation, and the Department of Energy, have programs to advance the technology. For example, engineers at the National Institute of Standards and Technology (NIST) are working to enhance additive manufacturing equipment and process metrology; process optimization and control; advanced sensor systems; materials characterization; data formats; and standards development.[93]

The U.S. federal government is also working with private industry and academic institutions to further advance additive manufacturing. NIST awards grants to improve additive manufacturing; it provided $7.4 million of funding in 2013.[94] The National Science Foundation has programs to educate students, workers, and enterprises about additive manufacturing. It also awards grants to improve the technology. The Department of Energy Advanced Manufacturing Office partners with industry, small businesses, and other stakeholders to identify and invest in additive manufacturing technologies. With the Oak Ridge National Laboratory, it has a program to develop advanced materials; implement advanced controls; and explore next-generation systems to overcome technology barriers for additive manufacturing. One project involves the development of large-scale, high-deposition-rate additive machining centers.[95]

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90 Scott et al., "Additive Manufacturing," March 2012, 11.

91 BioPortfolio, "Additive Manufacturing Techniques for Producing Tissue," July 22, 2013.

92 Levy, "A Fully Functional 3-D Printed Heart," April 15, 2014.

93 Slotwinski, "Additive Manufacturing at NIST," March 9, 2013, 2.

94 Bello, "NIST Awards $7.4 Million in Grants for Additive Manufacturing Research," September 2013 (accessed October 8, 2013).

95 Dehoff, "Thinking Beyond Today," July 11, 2013.

BOX 2 Initiatives in Other Countries

Industrialized economies, and a few developing ones, are working to develop and apply additive manufacturing, and thus strengthen productivity and competitiveness.

China, Singapore, and some countries in Europe have committed hundreds of millions of dollars to develop and commercialize additive manufacturing. China, for example, has been investing in additive manufacturing since the early 1990s, and the Chinese government is pledging 1.5 billion yuan ($245 million) to a seven-year project to advance development of the technology.a The Asian Manufacturing Association,[a] Beijing-funded trade group, is promoting wider integration of additive manufacturing by establishing 10 innovation institutes, each starting with a $3.3 million injection of investment.[b] A company in Hefei, Anhui Province, is investing 750 million yuan ($125 million), indicating that Chinese business is eager to explore the technology.[c]

Singapore is investing $500 million in additive manufacturing over the next five years.[d] The Singaporean government is dedicating significant funding to specific programs to help engineers define and use next-generation manufacturing technologies, and to explore the potential of building a new additive manufacturing industry ecosystem.[e]

There are also numerous efforts to further additive manufacturing in Europe. One initiative is the Direct Manufacturing Research Center at the University of Paderborn in Germany. Established in 2008, this institution is a leading research center for additive manufacturing, with funds from the German state of North Rhine-Westphalia and member companies. Research has thus far focused on improving the processes for laser sintering/melting technology for metal and plastic powder, as well as establishing industry requirements for materials, training, and standards development.[f] In October 2012, the UK government announced grants for collaborative research and development projects in additive manufacturing. The grants will be awarded through an open competition managed by the Technology Strategy Board, the Engineering and Physical Sciences Research Council, and the Economic and Social Research Council.[g]

[a] Brooke, "China Flexes Muscles," June 27, 2013.
[b] Brooke, "China Flexes Muscles," June 27, 2013.
[c] With the exception of Japan, additive manufacturing started much later in Asia than in the United States and Europe. Asia has largely caught up with the rest of the world; however, most industrial machines there are bought by product development companies to assist in early product development rather than final goods. Brooke, "China Flexes Muscles," June 27, 2013.
[d] Brooke, "Singapore to Invest," March 27, 2013.
[e] Brooke, "Singapore to Invest," March 27, 2013.
[f] Direct Manufacturing Research Center website, http://dmrc.uni-paderborn.de/about-dmrc (accessed July 5, 2013).
[g] The Engineer, "£7m Funding for UK Additive Manufacturing Projects," October 23, 2012.

America Makes, formerly the National Additive Manufacturing Innovation Institute (NAMII)—a public-private partnership with member organizations from government, industry, and academia—is a particularly robust additive manufacturing program.[96] America Makes is the flagship of 15 manufacturing institutes developed by the National Network for Manufacturing Innovation, a billion-dollar initiative to strengthen U.S. manufacturing and competitiveness.[97] The stated mission of America Makes is "to accelerate additive manufacturing technologies to the U.S. manufacturing sector and increase domestic manufacturing competitiveness."[98] It is promoting the technology by:

- establishing a collaborative network for sharing information and research;
- facilitating the development and application of efficient additive manufacturing technologies; and
- developing a workforce that can adapt to the changing requirements of additive manufacturing technologies and practices.[99]

America Makes is the first national program dedicated to additive manufacturing. It was launched in 2013 with $90 million in funding: $30 million from the federal government and the rest from the business and nonprofit sectors. The 20 projects underway range from basic research about how polymers and other materials will react during the heating and deposition process to work on more industrial applications, such as developing a lower-cost, high-temperature process for working with thermoplastics to make air and space vehicle components.[100]

Industry is taking steps to facilitate the development of additive manufacturing.[101] EWI, a non-profit engineering and technology resource organization, launched the Additive Manufacturing Consortium (AMC) in 2010. The AMC is a diverse group of practitioners and stakeholders working to "accelerate the innovation in additive manufacturing technologies to move them into the mainstream of manufacturing technology from their present emerging position."[102] Stratasys, Ltd. is working with the Oak Ridge National Laboratory to develop fused deposition

[96] In January 2013, the Brookings-Rockefeller Project on State and Metropolitan Innovation put NAMII on its annual "Top 10 State and Metropolitan Innovations to Watch" list, recognizing its potential to create jobs, grow regional economies, and boost global competitiveness.

[97] America Makes website, *https://americamakes.us/* (accessed June 13, 2013).

[98] America Makes website, *https://americamakes.us/* (accessed June 20, 2013).

[99] America Makes website, *https://americamakes.us/* (accessed June 13, 2013).

[100] America Makes website, *https://americamakes.us/* (accessed June 20, 2013).

[101] The United States dominated basic research for additive manufacturing through the late 1990s, when public funding decreased. Today, Europe, especially Germany, dominates applied research in the technology. Industry representative, interview by author, July 15, 2013.

[102] EWI is a member organization which develops and applies manufacturing technology innovation within the manufacturing industry. EWI, Additive Manufacturing Consortium website, *http://ewi.org/additive-manufacturing-consortium* (accessed June 20, 2013).

modeling[103] and make it a mainstream manufacturing practice.[104] Firms are also partnering with academia to promote additive manufacturing. Jet engine manufacturer Aerojet Rocketdyne, for example, is collaborating with the University of Connecticut to create one of the country's most state-of-the-art additive manufacturing facilities. Over the next five years, Aerojet Rocketdyne will invest $9 million in the development of powder-based additive manufacturing technologies.[105] These and other efforts aim to accelerate U.S. development and application of additive manufacturing technology and will likely help strengthen U.S. competitiveness.

Challenges to Development and Adoption

Several fundamental challenges must be addressed to achieve widespread use of additive manufacturing and to realize its potential economic benefits. Among the most significant challenges are developing standards, improving the selection and affordability of materials, and increasing the reliability and accuracy of equipment and processes.[106]

Standards Development

Developing standards is critical to increasing diffusion and adoption of the technology.[107] Standards would provide a foundation for creating products that conform to certain specifications and are compatible with products provided by different suppliers seeking the same quality, performance, and interchangeability.[108] Additive manufacturing standards would also ensure the safety, reliability, and quality of processes and products. Because there are currently only a handful of additive manufacturing standards, companies conduct their own testing to ensure integrity of the equipment, processes, and products.[109] Costly and time-consuming, testing deters wider application of additive manufacturing, underscoring the need to develop standards from design to part build to operation. A standard is needed, for example, for software compatibility and communication across additive manufacturing machines. Instead of a standard format for electronic blueprints that allows CAD programs to talk to each other, there are a number of proprietary and ad hoc formats that do not work well together, slowing and limiting production.[110]

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[103] Fused deposition modeling heats thermoplastic material to a semi-liquid state and extrudes it according to computer-controlled paths. The resulting parts are unrivaled in mechanical, thermal, and chemical strength.

[104] Grimm, "Stratasys and Oak Ridge," July 7, 2012.

[105] Photonics.com, "Pratt & Whitney Opens Additive Manufacturing Center," April 11, 2013; Aerojet Rocketdyne acquired Pratt & Whitney Rocketdyne in June 2013.

[106] Sealy, "Additive Manufacturing as a Disruptive Technology," 2012, 92.

[107] Scott et al., "Additive Manufacturing: Status and Opportunities," March 2012, 20.

[108] Scott et al., "Additive Manufacturing: Status and Opportunities," March 2012, 20.

[109] The adoption of parts made via additive manufacturing processes into critical applications, such as aerospace engine components, is hampered by a lack of consensus (e.g., regarding material properties for additive manufacturing) required for many procurement specifications; the NIST Materials Data Program provides evaluated data on phase equilibria, structure and characterization, and performance properties.

[110] Industry representative, interview by author, July 15, 2013.

Another area of additive manufacturing production that would benefit from standards development is material property data generation.[111] Measurement (metrology) capacity, among others, is severely lacking. Experts report that there is a "striking dearth of metrology capabilities for process-structure-property relationships; closed-loop and adaptive control systems; and new sensors for fundamental build properties such as shape and surface finish."[112] They further note critical needs in measuring the raw material inputs, processes, and resulting parts.[113]

All material property data must be robust and comprehensive. In 2009, in response to the need for industry standards, the Society of Manufacturing Engineers and ASTM International (formerly the American Society for Testing Materials) formed Committee F42 on Additive Manufacturing Technologies. The Committee, of which NIST is an executive member, is working to develop standards to:

- allow manufacturers to measure and compare the performance of different additive manufacturing processes and materials;
- specify part-building requirements to give purchasers and suppliers a common set of parameters with which to work, thereby improving vendor relationships;
- help new users adopt additive manufacturing technologies; and
- provide users with uniform procedures for calibrating additive manufacturing machines and testing their performance. [114]

The NIST Engineering Laboratory reports that the additive manufacturing industry has identified many additional needs for standards that will take much effort and time to develop.[115]

Material Selection and Cost

The narrow selection of inputs and uncertain properties of additively manufactured materials present barriers to many industries. This is especially true in aerospace, which needs material that can withstand staggering pressures and temperatures of over 2,000 degrees Fahrenheit.[116]

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[111] Property data summaries are collections of property values derived from surveys of published data. These collections typically focus on either one material or one particular property. Studies of specific materials typically include thermal, mechanical, structural, and chemical properties, while studies of particular properties survey one property across many materials. The property values may be typical, evaluated, or validated. Values described as typical are derived from values for nominally similar materials. Jurrens, "NIST Measurement Science for Additive Manufacturing," March 14, 2013, 7.

[112] Campbell and Slotwinski, "Metrology for Additive Manufacturing," 2013, 164.

[113] Campbell and Slotwinski, "Metrology for Additive Manufacturing," 2013, 163.

[114] Additive Manufacturing Institute, "Manufacturing Engineering," January 5, 2013, 16.

[115] NIST representative, interview by author, June 25, 2013.

[116] Georgia Technical Institute representative, interview by author, June 25, 2013.

Despite recent progress in additive manufacturing material development and characterization,[117] problems remain, including the limited selection of materials, inconsistent production quality, and high costs. As a result, only a fraction of the materials that are used in conventional manufacturing are compatible with additive manufacturing.[118] As noted earlier, the major categories of additive manufacturing materials are plastics and other polymers and metals. There are also diverse filled and composite materials, as well as ceramic and ceramic-metal hybrids.[119] According to NIST, "material requirements are impacted by the need to create feedstock, to be processed successfully by the fabricator coupled with post processing, and to manifest acceptable service qualities."[120]

Most additive manufacturing processes use proprietary polymers that are not well characterized, are often weaker than those used in traditional manufacturing, and can sometimes lack uniform part strength. Parts that have been additively manufactured with metal have physical properties that can be quite different from conventional wrought or cast metals. They may, for example, lack full density, which can compromise fracture toughness and fatigue properties. According to an industry expert, "porosity, or partial delamination, could act as crack initiation sites in the material, which could lead to premature failure of such parts, especially when subjected to cyclic stress conditions."[121]

Although there have been increases in the variety and application of additive manufacturing material inputs and feedstocks, they are still expensive relative to traditional manufacturing materials. For example, powder metals can be 200 times as costly as sheet metal,[122] and photopolymers cost $750–$1,000 per gallon, compared to injection molding material, which costs $1 per pound.[123] While some producers enjoy savings when using additive manufacturing for custom products and low production runs, high material prices continue to be an impediment for many potential producers.

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[117] Characterization in materials science refers to the use of external techniques to probe the internal structure and properties of a material (e.g., testing or analyzing a material to visualize its internal structure and gain knowledge about the distribution and interaction of its elements).

[118] The most common additive manufacturing materials are metals and plastics and/or polymers. Various filled and composite materials are also used, as well as ceramic and ceramic-metal hybrids. The most common traditional manufacturing materials are metal, ceramics, and polymers. The Library of Manufacturing website, *http://thelibraryofmanufacturing.com* (accessed May 21, 2014).

[119] The versatility of what can be made will grow exponentially with the increasing number of primary materials that can be simultaneously mixed and printed. Hybrids are not just mixed materials; they are new kinds of materials with unique properties.

[120] Bourell, Leu, and Rosen, *Roadmap for Additive Manufacturing*, 2009, 31.

[121] Wohlers, *Wohlers Report 2012*, 2012, 78; Campbell and Slotwinski, "Metrology for Additive Manufacturing," 2013, 167. The layer-wise nature of various additive manufacturing processes can lead to unwanted levels of porosity, especially for processes that involve melting of input materials. Porosity is beneficial for some biomedical implants, but can cause metal aerospace parts to fail.

[122] McKinsey Global Institute, *Manufacturing the Future*, 2013, 90.

[123] Gordon, "Building Strong but Lightweight," October 1, 2011, 7.

Equipment and Processes

Establishing additive manufacturing as a mainstream technology is, in part, contingent upon overcoming significant constraints in equipment and processes. Limitations such as machine cost and software capability will likely be overcome in the medium term.[124] Indeed, prices of industrial machines are falling, and capabilities of software and scanning devices are improving. Other limitations, however, are less likely to be surmounted soon.[125] The physics of layering and curing, for example, impose limits on process speed. Additionally, the issue of minimum wall thickness[126] is a fundamental restraint that is unlikely to be resolved without significant technological advancement.[127]

The *Roadmap for Additive Manufacturing*,[128] developed by experts in academia, government, and industry, outlines the following technological barriers:

- High costs of machinery and materials in comparison to those used in conventional manufacturing;
- Product fabrication speeds that are significantly slower than mass production processes;[129]
- Inherent tradeoffs between product size, accuracy, and speed (e.g., larger surfaces entail lengthier production times; accelerated production processes may produce parts with unknown and unpredictable properties);
- Significant geometric and property variations between "identical" products built on different machines leading to a lack of repeatability (e.g., use of the same materials and identical CAD files on five different machines could produce five goods with different properties);
- Requirements for highly skilled operators and/or careful periodic tuning, both of which are in short supply and costly;
- Unreliable machinery and inconsistent product quality, particularly with regard to part accuracy and surface finishes;
- Closed architectures, which preclude researchers from making meaningful changes to processing conditions; and
- The lack of hardware and software necessary for simple and effective multi-material deposition.[130]

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[124] The average industrial additive manufacturing machine now sells for about $75,000, and some machines cost more than $1 million. McKinsey & Co., *Disruptive Technologies*, 2013, 109.

[125] Limitations vary by additive manufacturing technique.

[126] Minimum wall thickness is the absolute minimal thickness of a pipe or structure to contain its contents.

[127] Deloitte, "TNT Predictions," March 17, 2012, 16.

[128] Bourell, Leu, and Rosen, *Roadmap for Additive Manufacturing*, 2009. This document was designed with the goal of developing and articulating a systematic plan for additive manufacturing research for the next 10–12 years. Other sources outlined the same barriers. In 2013, America Makes announced plans to develop a national additive manufacturing roadmap.

[129] Rapid prototyping is quicker with additive manufacturing.

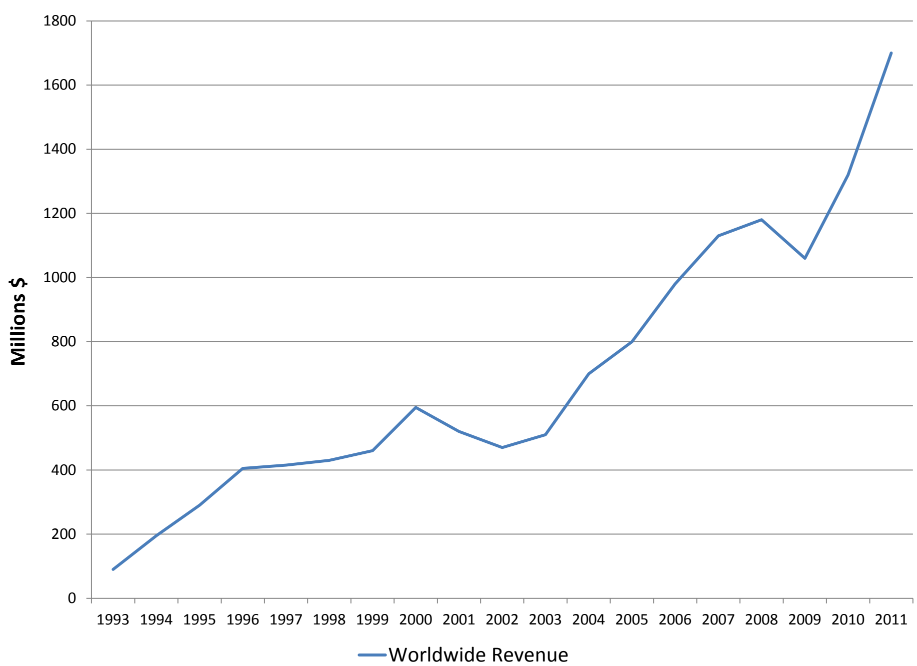
[130] Bourell, Leu, and Rosen, *Roadmap for Additive Manufacturing*, 2009, 16.

INDICATORS OF FUTURE GROWTH

Increasing sales, technological advances, new applications, and the expiration of key patents are indicators of likely continuing growth in additive manufacturing. They are also drivers of the market, fueling momentum in investment, development, and applications.

The world market for additive manufacturing equipment and services has steadily and rapidly expanded since the mid-1980s. Wohlers Associates reports that in 15 of the 24 years it has tracked the technology, revenue[131] in the primary additive manufacturing market grew in the double digits and, in 2011, increased an estimated 29.4 percent to $1.7 billion[132] (figure 3). This estimate comprises all products and services directly associated with additive manufacturing processes worldwide.[133] Product revenue of $834 million includes additive manufacturing machines, machine upgrades, materials, and aftermarket products such as third-party software

FIGURE 3 Worldwide revenue for additive manufacturing products and services, 1993–2011



Source: Wohlers, *Wohlers Report 2012*, 2012, 125-127.

[131] Neither category includes secondary processes, such as making castings from this tooling. This market segment grew 25.1 percent, to $1 billion in 2011, up from $836 million in 2010, when it grew 27.3 percent. The combined total for overall additive manufacturing products and services—both primary and secondary markets—was $2.8 billion, an increase of 27.4 percent from $2.2 billion generated in 2010. Wohlers, *Wohlers Report 2012*, 2012, 130.

[132] Wohlers, *Wohlers Report 2012*, 2012, 125.

[133] Wohlers Associates considers and reports the secondary market segment separately.

and lasers.[134] Services revenue includes $642.6 million from parts produced on additive manufacturing machines by service providers, such as replacement components and $236.9 million from machine maintenance contracts and activities such as training, seminars, conferences, contract research, and consulting.[135]

Revenue is expected to continue strong double-digit growth over the next several years, with sales of additive manufacturing products and services likely reaching $3.7 billion worldwide by 2015 and surpassing $6.5 billion by 2019.[136]

The United States leads in the production and sales of professional-grade industrial additive manufacturing machines, accounting for 38 percent of installed machines during 1998–2011 (figure 2). Nearly two-thirds of all the industrial machines sold in 2011 came from U.S. manufacturers.[137] Wohlers Associates reports that annual sales of professional-grade, industrial additive-manufacturing machines will exceed 10,000 units worldwide by 2016.[138] Machines priced in the $5,000–$25,000 range will be responsible for most of this growth.[139] The growth reflects industry developments in and increasing awareness of additive manufacturing.

Advances in Materials

As discussed above, the range of feedstock applications available for use in additive manufacturing pales in comparison to that for traditional manufacturing. Over the past five years, however, significant improvements have occurred in the properties, variety, and quality of the applications for additive manufacturing.[140] It is now possible, for example, to additively manufacture parts in a range of metals that are on par with wrought material and exceed the properties of castings.[141] Among the available metals for additive manufacturing are aluminum alloys, titanium alloys, nickel-based superalloys, and a range of steels. Engineers are able to additively fabricate fully functional components from titanium and various steel alloys, featuring material properties that are equivalent to their traditionally manufactured counterparts. "Direct metal" processes will continue to advance as process control and understanding of fundamental metallurgy for additive manufacturing improves. Recent work at the Fraunhofer Institute for Laser Technology points to the potential for a fourfold increase in printing speeds for metal objects.[142]

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[134] Wohlers, *Wohlers Report 2012*, 2012, 126. The average selling price of an industrial additive manufacturing machine was $73,220 in 2011; Wohlers, *Wohlers Report 2012,* 2012, 127.

[135] Wohlers, *Wohlers Report 2012,* 2012, 130.

[136] Wohlers, *Wohlers Report 2012*, 2012, 131.

[137] IBISWorld, "3D Printer Manufacturing Market Research Report," December 2012, 18.

[138] Wohlers, *Wohlers Report 2012*, 2012, 131.

[139] Wohlers, *Wohlers Report 2012*, 2012, 137.

[140] Metals, plastics, and other feedstock require special processing (e.g., polymerization) for use in additive manufacturing.

[141] Wohlers, *Wohlers Report 2012*, 2012, 79.

[142] McKinsey Global Institute, *Disruptive Technologies*, 2013, 109.

The increase, if achieved, would make additive manufacturing more attractive to a wider range of industries—and more competitive with traditional manufacturing.

The variety and quality of plastic, ceramic, and hybrid materials for additive manufacturing also continues to increase. EOS GmbH recently released three new polymers for its powder bed fusion process. PrimePart and the French chemical company Arkema have begun marketing two nylon-based powders designed for easy processing.[143] Scientists at General Electric Global Research and designers at General Electric Aviation have developed a group of new materials, ceramic matrix composites (CMC). Additively manufactured CMC components outperform the most advanced metallic alloys in gas turbines for jet aircraft.[144] CFM International, a joint venture between General Electric Aviation and France's Snecma, completed designs for a jet engine that includes additively manufactured ceramic matrix composites. CFM plans to build the first engine in 2014, and to test and certify it over the next two years.[145]

As a result of breakthroughs in multi-material additive manufacturing, more complex materials are being produced. The Objet Connex500, for example, additively manufactures up to 14 plastic-like materials in one job run. Rather than being fabricated as separate components and attached one at a time, they are simultaneously fused together. Researchers are developing new materials such as high-temperature polymers integrated with optics gradient materials, in situ sensors,[146] self-assembled single crystals, and continuous-filament composites.[147] The growing number and variety of materials for additive manufacturing increases the range of possible users and applications.

New Design Tools

New design tools specific to additive manufacturing are proliferating. Until recently, inputs into an additive manufacturing machine were limited to a CAD model. Now, input can be generated by a number of means, including medical scan data, entertainment software (as is the case with computer game avatars), and even simple drawing and sketching programs.[148]

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[143] Rilsan Invent Natural and Rilsan Invent Black. Wohlers, *Wohlers Report 2012*, 2012, 76.

[144] Ceramic matrix composites handle enormous stress and temperatures as high as 2,400 degrees Fahrenheit inside gas turbines and jet engines, and make them much more fuel efficient. CFM estimates that the reduced weight of the additively manufactured components will reduce fuel consumption by about 15 percent—enough to save nearly $1 million per year per airplane, assuming a fuel cost of $2.50 per gallon. Destefani, "Ceramic Matrix Composites Make Inroads in Aerospace," May 14, 2013, 1.

[145] GE Reports, "Design Freeze Brings Next-Gen LEAP Engine," May 6, 2013, 2.

[146] *In situ* sensors are in constant contact with the medium they are measuring. For example, a spectroscopic sensor detects and categorizes defects, predicts the composition and phase transformation of the medium, and monitors manufacturing quality in real time.

[147] Objet Connex website, *http://www.stratasys.com/3d-printers/design-series/precision/objet-connex500* (accessed July 2, 2013).

[148] Wohlers, *Wohlers Report 2012*, 2012, 22.

Software and design tools such as Autodesk 123D Suite are becoming increasingly popular.[149] The growing sophistication of the tools will enable production of new, complex designs as well as the analytical techniques to validate the designs before manufacturing.

Future design tools will be created to be intuitive to use. Some, for example, will respond to touch and movement; others will respond to environmental conditions.[150] Co-design and co-creator tools are also emerging and can often be accessed and used on a website. With the advent of more advanced design tools, the benefits of additive manufacturing, such as prototyping, can be more fully realized and may spur new products and innovations.[151]

Expiration of Key Patents

The expiration of early additive manufacturing machinery patents is influencing the development of new machines and applications in the United States and abroad. When the original fused deposition modeling patent expired in 2005, it allowed for the creation of RepRap, a replicating rapid prototyper. RepRap was the first low-cost additive manufacturing machine and it has found great popularity in the open-source community. Today, RepRap is more widely used than any other additive manufacturing system.[152]

The last of the selective laser sintering[153] patents from inventor Dr. Carl Deckard and the University of Texas at Austin expired in June 2014. Wohlers Associates report that plans to produce a more affordable alternative are already underway. They suggest that there will be several new developments based on laser sintering technology by mid-2014.[154] As more patents expire, there will be opportunities to capitalize on the technology and to develop new systems. These new systems will likely provide additional product offerings and increase competition among manufacturers.

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[149] Wohlers, *Wohlers Report 2012*, 2012, 199.

[150] Lipson and Kurman, *Fabricated*, 2013, 221.

[151] Bourell, Leu, and Rosen, *Roadmap for Additive Manufacturing*, 2009, 16.

[152] RepRap website, *http://reprappro.com/about* (accessed July 2, 2013).

[153] Selective laser sintering involves the use of a high-powered laser (for example, a carbon dioxide laser) to fuse small particles of plastic, metal (direct metal laser sintering), ceramic, or glass powders into a mass that has a desired three-dimensional shape.

[154] Wohlers, *Wohlers Report 2012*, 2012, 253. Selective laser sintering can easily make very complex geometries directly from digital CAD data. While it began as a way to build prototype parts early in the design cycle, it is increasingly being used in limited-run manufacturing to produce end-use parts.

POTENTIAL IMPLICATIONS FOR MANUFACTURING COMPETITIVENESS

Additive manufacturing is increasingly used in the automotive, medical, and aerospace industries, but largely remains limited to small-series production within them. While the technology has room to grow and potential to strengthen productivity in many industries, its implications for overall manufacturing competitiveness are less clear. As with any emerging technology, new standards, wider awareness, and a better-developed infrastructure are required to facilitate its use.[155] Further, evolving industry and government policy—as well as the convergence of additive manufacturing with other advancing technologies—will certainly bolster the use of additive manufacturing.

Impacts on Manufacturing

It is difficult to predict in detail how additive manufacturing—a technology that is still emerging—will affect individual industries. However, if challenges and barriers noted earlier can be overcome, additive manufacturing has the potential to open the door to myriad new processes and efficiencies. The impacts will initially be limited to a range of customized, small-batch production goods, but there are indications that a paradigm shift has already started. Some likely impacts include:

- reduced material waste in comparison to subtractive methods;
- superior products with complex internal structures that add strength, reduce weight, increase functionality, and are easier to maintain;
- open-design products created by communities of end users; and
- customization as per-unit costs of small production runs (even single items) approach those of long runs.[156]

As additive manufacturing continues to evolve, it will likely result in:

- quicker time to market due to faster design and prototyping cycles as well as the possible elimination of many traditional manufacturing steps such as transportation, tooling, and assembly;
- greater competition, creating a larger variety of products due to lowered barriers to entry; and
- smaller, less costly, and more agile supply chains, especially for low-volume or highly specialized components.[157]

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155 Thomas, *Economics of the U.S. Additive Manufacturing Industry* (prepublication draft), June 2013, 2.

156 CSC, "3D Printing and the Future of Manufacturing," Fall 2012, 21.

157 CSC, "3D Printing and the Future of Manufacturing," Fall 2012, 21.

CONCLUSION

Despite the challenges to further adoption, many experts believe additive manufacturing will significantly change certain production and distribution activities. The Economist predicts the technology will have an impact on manufacturing as profound as modern assembly-line factories did in the 20th century.[158] The McKinsey Global Institute notes that "the technology could usher in a new ecosystem of smaller value chains and new companies providing printable designs on the web, instead of products on the shelf . . . small business will be able to compete with traditional manufacturing, product will never go out of stock, size of batches will become meaningless, and manufacturing will become truly just in time."[159]

The United States is already a leader in the production and use of additive manufacturing. With one of the most innovative and flexible economies in the world, it is also well positioned to further exploit the technology.[160] Additive manufacturing could reduce costs and improve efficiency in manufacturing, which continues to be an important driver of prosperity in the country: manufacturing accounts for 12 percent of U.S. gross domestic product, 70 percent of private R&D spending, 60 percent of exports, and about a third of productivity growth. The establishment of standards and appropriate government and industry policies and initiatives would accelerate development and adoption of the technology. Although the benefits would vary according to industry, the resulting spillover effects would likely enhance the overall productivity and manufacturing competitiveness of the United States.

[158] *Economist*, "Print Me a Stradivarius," April 21, 2012, 17.

[159] Baily, Manyika, and Gupta, "U.S. Productivity Growth: An Optimistic Perspective," Spring 2013, 8.

[160] As noted, among the countries for which OECD STAN data are available, for example, the United States also has the largest R&D expenditure for total manufacturing growth.

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