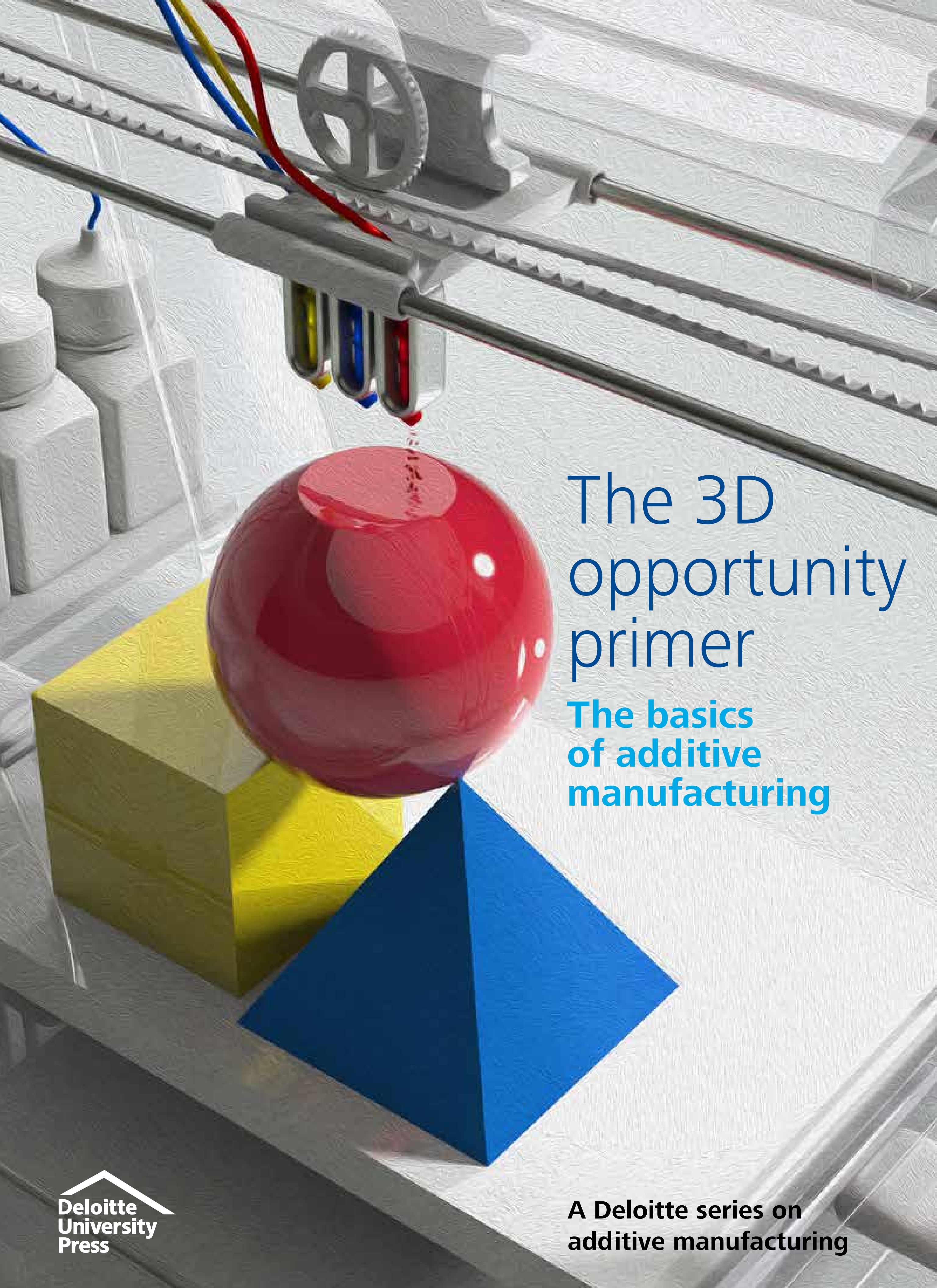

The 3D opportunity primer

The basics of additive manufacturing

A Deloitte series on additive manufacturing

Deloitte University Press

Contents

Foreword

ADDITIVE manufacturing (AM), also known as 3D printing, refers to a group of technologies that create products through the addition of materials (typically layer by layer) rather than by subtraction (through machining or other types of processing).

The history of AM traces back over 30 years to 1983 and the invention of stereolithography. Since then, the technology has evolved to include at least 13 different sub-technologies grouped into seven distinct process types.

We hope this report serves as a useful primer for managers seeking to develop a basic understanding of the different technologies and processes that fall under the AM umbrella. Although not exhaustive (as the technologies are constantly evolving), we believe this report offers a thorough survey to facilitate enlightened discussion by companies interested in the AM topic.

To help readers appreciate how AM can aid their companies' performance, growth, and innovation goals, we offer a detailed framework in our report *3D opportunity: Additive manufacturing paths to performance, innovation, and growth*, available on Deloitte University Press.[1] We also offer specific insights for key industries: *3D opportunity for aerospace and defense: Additive manufacturing takes flight* (http://dupress.com/articles/additive-manufacturing-3d-opportunity-in-aerospace/); *3D opportunity for the automotive industry: Additive manufacturing hits the road* (http://dupress.com/articles/additive-manufacturing-3d-opportunity-in-automotive/); and *3D opportunity in medical technology: Additive manufacturing comes to life* (http://dupress.com/articles/additive-manufacturing-3d-opportunity-in-medtech/). For a complete catalog of material available from Deloitte on additive manufacturing, please see http://dupress.com/collection/3d-opportunity.

An overview of additive manufacturing (3D printing)

Additive manufacturing (AM) defined

ADDITIVE manufacturing (AM) refers to a set of technologies and processes that have been developed over more than 30 years. ASTM International, a global body recognized for the development and delivery of consensus standards within the manufacturing industry, defines additive manufacturing as:

> "A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.[2]"

In common practice, the terms "AM" and "3D printing" are used interchangeably.[3]

AM process flow: Layer-by-layer additive process

The AM process traditionally begins with the creation of a three-dimensional (3D) model through the use of computer-aided design (CAD) software. The CAD-based 3D model is typically saved as a standard tessellation language (.STL) file, which is a triangulated representation of the model. Software then slices the data file into individual layers, which are sent as instructions to the AM device. The AM device creates the object by adding layers of material, one on top of the other, until the physical object is created. Once the object is created, a variety of finishing activities may be required. Depending on the material used and the complexity of the product, some parts may need secondary processing, which can include sanding, filing,

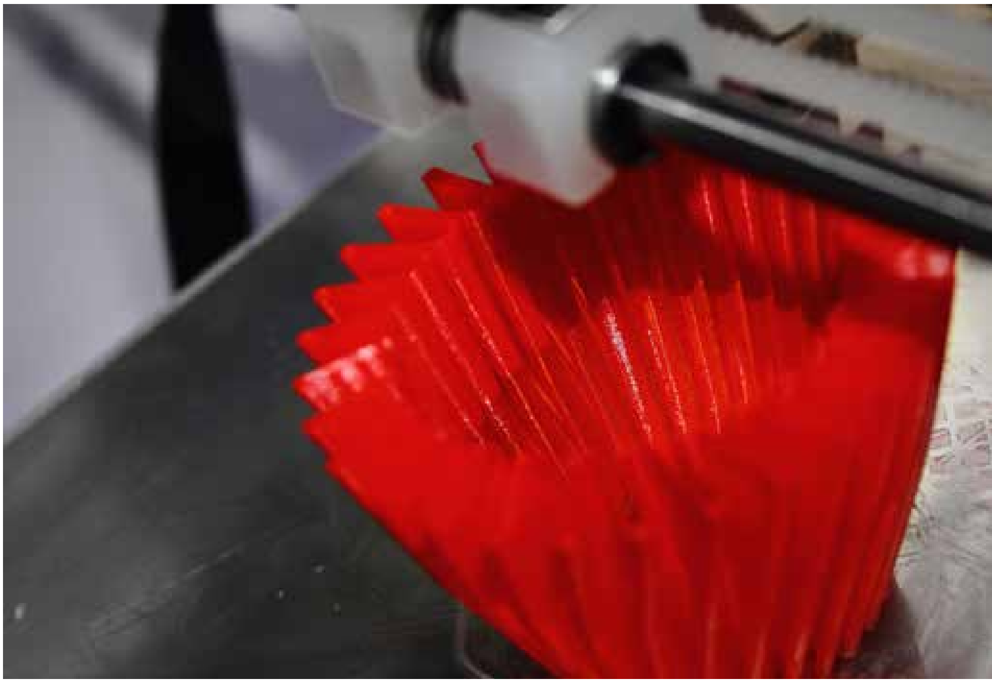

Figure 1. Examples of components fabricated using additive manufacturing

Photos used by permission of 3D Systems.

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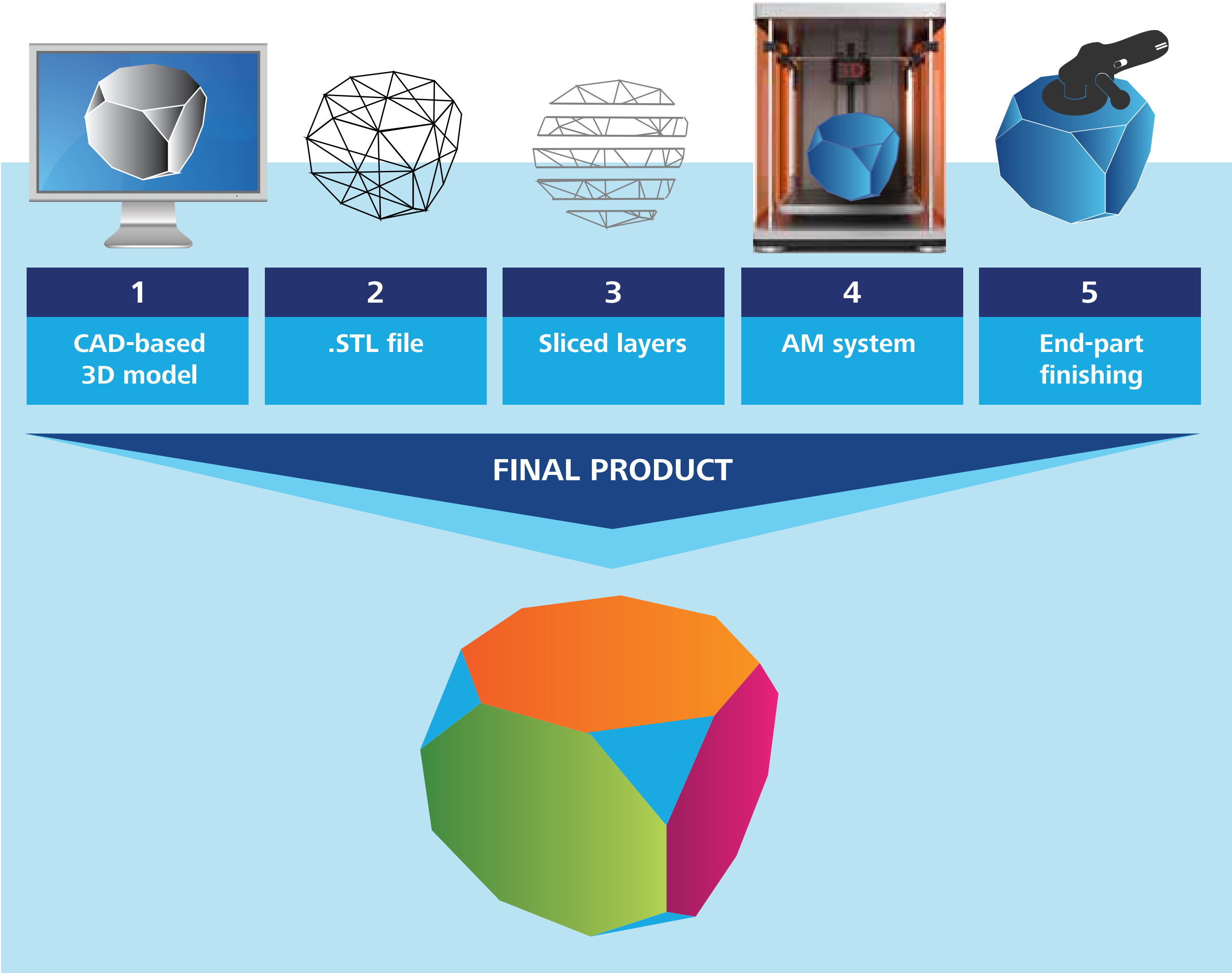
Figure 2. Additive manufacturing (AM) process flow



Graphic: Deloitte University Press | DUPress.com

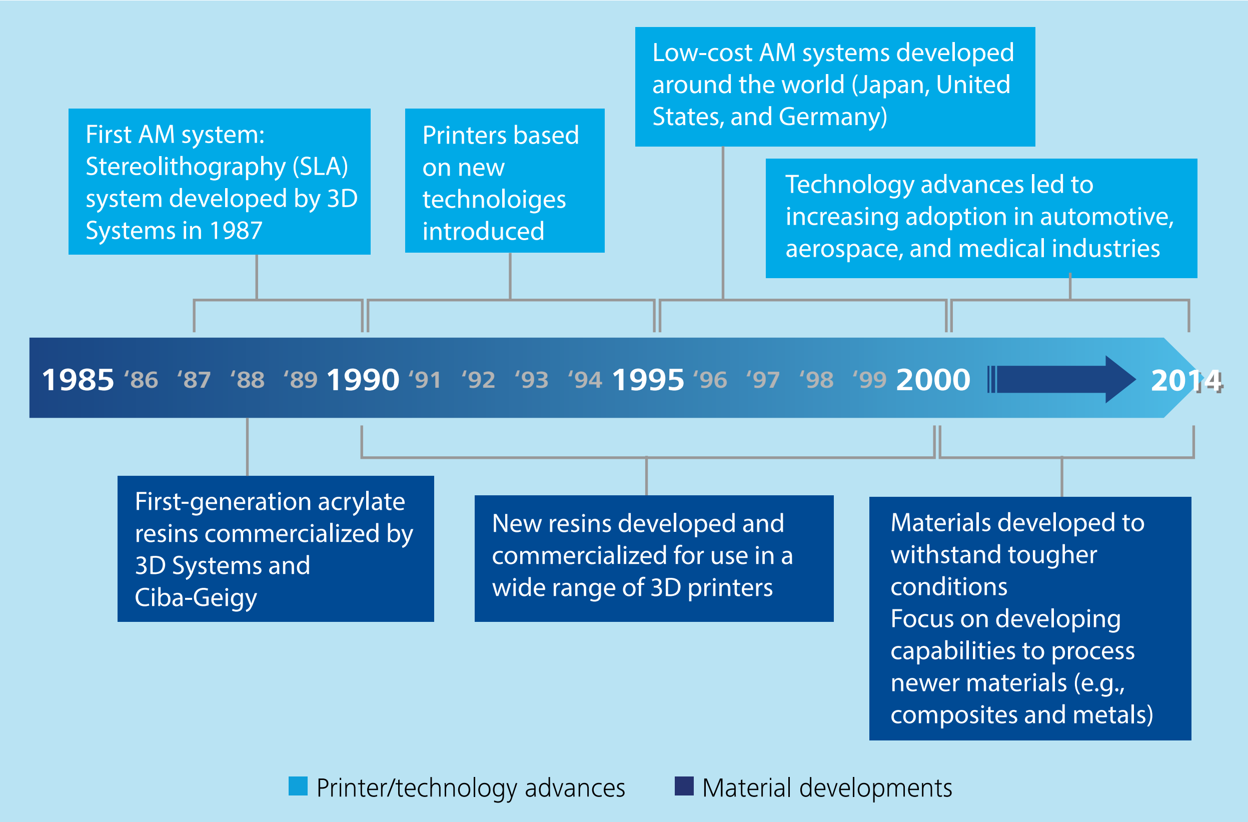
polishing, curing, material fill, or painting. Figure 1 depicts a selection of items manufactured using AM. Figure 2 depicts the overall AM process.

Sophisticated 3D scanning and imaging tools are emerging as alternatives for traditional CAD programs. In addition, stylus-based and other design technologies that allow consumers to modify digital models themselves—without the need for extensive CAD experience—are expected to drive growth in the personal AM systems space. New formats, such as additive manufacturing file format (AMF), are also being developed to address .STL's limitations and allow for more flexible file structures.

History of additive manufacturing: Industry adoption accelerates in the past decade

AM has its earliest roots in research activities from the fields of topography and photosculpture during the 19th century. The first successful attempts at AM derived from technology developed in the 1970s.[4] AM first approached commercial viability in 1983 when Charles Hull invented stereolithography, enabling a 3D object to be printed from CAD data.[5] In 1986, Hull co-founded 3D Systems, Inc., the first company to commercialize AM technology with the stereolithography (SLA)

Figure 3. Evolution of additive manufacturing technology



Source: Deloitte analysis; Wohlers Associates, *Additive manufacturing and 3D printing state of the industry*, 2012; The University of Texas at Austin, "Selective laser sintering, birth of an industry," December 7, 2012, http://www.me.utexas.edu/news/2012/0712_sls_history.php, accessed January 25, 2014.

Graphic: Deloitte University Press | DUPress.com

apparatus.[6] Selective laser sintering (SLS), another AM technology, was first commercialized in the late 1990s; just like SLA, its applications grew from prototyping to end-part production over the years, driven by lower system costs.[7]

AM processes were largely geared toward prototyping applications in the 1990s. However, since the late 1990s, AM technologies and processes have increasingly been deployed to large-scale industrial, medical, and consumer end-market applications. Significant developments since the early 2000s include AM applications in the production of parts for unmanned aircraft, automobiles, consumer products, and organ and tissue printing systems.[8] As shown in figure 3, AM technology continues to improve in the speed of processing, the complexity of design, and the variety of materials used.

AM versus traditional manufacturing: Understanding trade-offs

AM creates 3D structures by adding materials layer upon layer. In contrast, traditional manufacturing practices (such as drilling or machining) are often "subtractive," as they remove material from areas where it is not desired. Additive manufacturing and traditional manufacturing face different trade-offs, with each process likely to play a role in the deployment of manufacturing capabilities.

Below, we list some of the respective advantages of AM and traditional manufacturing.

Advantages of AM

- **Design complexity:** AM enables the creation of intricate designs to precise dimensions that are difficult or impossible to create using traditional methods.

- **Speed to market:** AM systems can manufacture products with little or no tooling, saving time during product design and development and enabling on-demand manufacturing.

- **Waste reduction:** AM typically uses less extraneous material when manufacturing components, thus significantly reducing or eliminating scrap and waste during production. This makes AM a more efficient process.

Advantages of traditional manufacturing

- **Mass production:** Traditional manufacturing is well-suited for high-volume production where fixed tooling and setup costs can be amortized over a larger number of units. Additive manufacturing is generally more competitive for low-to-medium volume production runs.

- **Choice of materials:** Traditional manufacturing techniques can be deployed to a wide variety of materials, while additive manufacturing predominantly uses a narrower range of polymers, metals, ceramics, and composites.

- **Manufacturing large parts:** Compared with AM systems, which are constrained by the envelope sizes currently available, traditional machining is better suited to manufacturing large parts.

Overall, AM offers companies an array of time efficiencies and cost reductions throughout the product lifecycle and supply chain, as well as greater flexibility in design and product customization than traditional manufacturing. These benefits will likely drive increasing levels of AM adoption going forward. Two key areas of benefit include:

- **Workflow streamlining:** AM can reduce prototype development time and shorten review cycles. Since AM processes are viewed as generating less scrap and using fewer tools, materials, and parts than traditional manufacturing—as well as reduced assembly and inventory demands—substantial cost benefits can be anticipated.

- **Flexible design and product customization:** AM processes offer rapid iteration of designs and enable low-volume print-on-demand applications. The ability to engage and influence the customer experience through custom, same-day production may have ramifications in consumer and industrial products end markets.

AM processes, technologies, and applications

FUNCTIONAL prototypes and end-use parts built through AM technologies have wide applications in industries such as industrial & consumer products, automotive, medical, and aerospace. AM technologies use a variety of materials, including plastics, metals, ceramics, and composites, and deploy multiple different processes to address issues such as design complexity, surface finish, unit cost, speed of operations, and others. To meet diverse requirements, industrial-grade AM systems are available in the market ranging in cost from less than $10,000 to $1 million—and more.[9]

AM technologies are typically based on one of the seven primary manufacturing processes described below.[10] The major AM processes and technologies can be characterized by the materials they use and the advantages and disadvantages they offer (figure 4).[11]

AM technologies use a range of materials. A classification of these materials into broad categories (figure 5) reveals that materials such

Vat photopolymerization
In vat photopolymerization, a liquid photopolymer (i.e., plastic) in a vat is selectively cured by light-activated polymerization. The process is also referred to as light polymerization. *Related AM technologies: Stereolithography (SLA), digital light processing (DLP)*
Material jetting
In material jetting, a print head selectively deposits material on the build area. These droplets are most often comprised of photopolymers with secondary materials (e.g., wax) used to create support structures during the build process. A UV light solidifies the photopolymer material to form cured parts. Support material is removed during post-build processing. *Related AM technologies: Multi-jet modeling (MJM)*
Material extrusion
In material extrusion, thermoplastic material is fed through a heated nozzle and deposited on a build platform. The nozzle melts the material and extrudes it to form each object layer. This process continues until the part is completed. *Related AM technologies: Fused deposition modeling (FDM)*
Powder bed fusion
In powder bed fusion, particles of material (e.g., plastic, metal) are selectively fused together using a thermal energy source such as a laser. Once a layer is fused, a new one is created by spreading powder over the top of the object and repeating the process. Unfused material is used to support the object being produced, thus reducing the need for support systems. *Related AM technologies: Electron beam melting (EBM), selective laser sintering (SLS), selective heat sintering (SHS), and direct metal laser sintering (DMLS)*
Binder jetting
In binder jetting, particles of material are selectively joined together using a liquid binding agent (e.g., glue). Inks may also be deposited in order to impart color. Once a layer is formed, a new one is created by spreading powder over the top of the object and repeating the process. This process is repeated until the object is formed. Unbound material is used to support the object being produced, thus reducing the need for support systems. *Related AM technologies: Powder bed and inkjet head (PBIH), plaster-based 3D printing (PP)*

Sheet lamination
In sheet lamination, thin sheets of material (e.g., plastic or metal) are bonded together using a variety of methods (e.g., glue, ultrasonic welding) in order to form an object. Each new sheet of material is placed over previous layers. A laser or knife is used to cut a border around the desired part and unneeded material is removed. This process is repeated until the part is completed. *Related AM technologies: Laminated object manufacturing (LOM), ultrasonic consolidation (UC)*

Directed energy deposition
In directed energy deposition, focused thermal energy is used to fuse (typically metal) material as it is being deposited. Directed energy deposition systems may employ either wire-based or powder-based approaches. *Related AM technologies: Laser metal deposition (LMD)*

Figure 4. AM technologies, corresponding base materials, and advantages and disadvantages

Technology	AM process	Typical materials	Advantages	Disadvantages
Stereolithography	Vat polymerization	Liquid photopolymer, composites	Complex geometries; detailed parts; smooth finish	Post-curing required; requires support structures
Digital light processing	Vat polymerization	Liquid photopolymer	Allows concurrent production; complex shapes and sizes; high precision	Limited product thickness; limited range of materials
Multi-jet modeling (MJM)	Material jetting	Photopolymers, wax	Good accuracy and surface finish; may use multiple materials (also with color); hands-free removal of support material	Range of wax-like materials is limited; relatively slow build process
Fused deposition modeling	Material extrusion	Thermoplastics	Strong parts; complex geometries	Poorer surface finish and slower build times than SLA
Electron beam melting	Powder bed fusion	Titanium powder, cobalt chrome	Speed; less distortion of parts; less material wastage	Needs finishing; difficult to clean the machine; caution required when dealing with X-rays
Selective laser sintering	Powder bed fusion	Paper, plastic, metal, glass, ceramic, composites	Requires no support structures; high heat and chemical resistant; high speed	Accuracy limited to powder particle size; rough surface finish
Selective heat sintering	Powder bed fusion	Thermoplastic powder	Lower cost than SLS; complex geometries; no support structures required; quick turnaround	New technology with limited track record
Direct metal laser sintering	Powder bed fusion	Stainless steel, cobalt chrome, nickel alloy	Dense components; intricate geometries	Needs finishing; not suitable for large parts
Powder bed and inkjet head printing	Binder jetting	Ceramic powders, metal laminates, acrylic, sand, composites	Full-color models; inexpensive; fast to build	Limited accuracy; poor surface finish
Plaster-based 3D printing	Binder jetting	Bonded plaster, plaster composites	Lower price; enables color printing; high speed; excess powder can be reused	Limited choice of materials; fragile parts
Laminated object manufacturing	Sheet lamination	Paper, plastic, metal laminates, ceramics, composites	Relatively less expensive; no toxic materials; quick to make big parts	Less accurate; non-homogenous parts

Figure 4. AM technologies, corresponding base materials, and advantages and disadvantages (cont.)

Technology	AM process	Typical materials	Advantages	Disadvantages
Ultrasonic consolidation	Sheet lamination	Metal and metal alloys	Quick to make big parts; faster build speed of newer ultrasonic consolidation systems; generally non-toxic materials	Parts with relatively less accuracy and inconsistent quality compared to other AM processes; need for post-processing
Laser metal deposition	Directed energy deposition	Metals and metal alloys	Multi-material printing capability; ability to build large parts; production flexibility	Relatively higher cost of systems; support structures are required; need for post-processing activities to obtain smooth finish

Sources: Deloitte analysis; Wohlers Associates, *Additive manufacturing and 3D printing state of the industry*, 2012; Troy Jensen and Pipar Jaffray, *3D printing: A model of the future*, March 2013; Justin Scott, IDA Science and Technology Policy Institute, *Additive manufacturing: status and opportunities*, March 2012.

Graphic: Deloitte University Press | DUPress.com

Figure 5. Technologies and materials matrix[12]

Technology	Polymers	Metals	Ceramics	Composites
Stereolithography	●			●
Digital light processing	●			
Multi-jet modeling (MJM)	●			●
Fused deposition modeling	●			
Electron beam melting		●		
Selective laser sintering	●	●	●	●
Selective heat sintering	●			
Direct metal laser sintering		●		
Powder bed and inkjet head printing[13]	●	●	●	●
Plaster-based 3D printing			●	●
Laminated object manufacturing[14]	●	●	●	●
Ultrasonic consolidation		●		
Laser metal deposition		●		●

Sources: Deloitte analysis; Wohlers Associates, *Additive manufacturing and 3D printing state of the industry*, 2012; Phil Reeves, *3D printing & additive manufacturing: Extending your printing capability in true 3D*, Econolyst, June 12, 2012; Justin Scott, IDA Science and Technology Policy Institute, *Additive manufacturing: Status and opportunities*, March 2012.

Graphic: Deloitte University Press | DUPress.com

as polymers and metals are widely used in AM systems. To a lesser extent, ceramics and composites also support AM processes. Use of varied materials in AM is an area of focus for R&D in the future.

AM applications: The technology's inherent benefits will drive increasing penetration across industries in the next decade

Application of AM technologies is expected to grow across industries as increasing numbers of companies use the technology not just for producing prototypes, but to manufacture parts and full-scale products.[15] The technology will act as a particularly strong catalyst for substantive research developments in the health care and manufacturing industries.[16] Figure 6 summarizes some current applications of and potential future developments in AM in select industries. The breadth of current and likely future applications suggests that there is strong growth potential for AM going forward.

Figure 6. AM applications by select end markets

INDUSTRIES	CURRENT APPLICATIONS	POTENTIAL FUTURE APPLICATIONS
COMMERCIAL AEROSPACE AND DEFENSE[17]	• Concept modeling and prototyping • Structural and non-structural production parts • Low-volume replacement parts	• Embedding additively manufactured electronics directly on parts • Complex engine parts • Aircraft wing components • Other structural aircraft components
SPACE	• Specialized parts for space exploration • Structures using light-weight, high-strength materials	• On-demand parts/spares in space • Large structures directly created in space, thus circumventing launch vehicle size limitations
AUTOMOTIVE[18]	• Rapid prototyping and manufacturing of end-use auto parts • Parts and assemblies for antique cars and racecars • Quick production of parts or entire	• Sophisticated auto components • Auto components designed through crowdsourcing
HEALTH CARE[19]	• Prostheses and implants • Medical instruments and models • Hearing aids and dental implants	• Developing organs for transplants • Large-scale pharmaceutical production • Developing human tissues for regenerative therapies
CONSUMER PRODUCTS/RETAIL	• Rapid prototyping • Creating and testing design iterations • Customized jewelry and watches • Limited product customization	• Co-designing and creating with customers • Customized living spaces • Growing mass customization of consumer products

Sources: Deloitte analysis; CSC, *3D printing and the future of manufacturing*, 2012.

Graphic: Deloitte University Press | DUPress.com

Market opportunities and challenges

IN his 2013 State of the Union address, US President Barack Obama called for the creation of the National Additive Manufacturing Innovation Institute (now called America Makes), established and funded in part by the US government, to help revitalize the US manufacturing sector.[20] AM has the potential to shift the US manufacturing paradigm in coming years; it can allow the United States to become self-sufficient as production becomes localized. Some experts have even heralded AM as the next great disruptive technology, similar to personal computing, giving everyone on the planet the ability to imagine, design, and create custom and personalized products.[21] Such exuberance should be tempered. Even as AM offers great potential, it also faces an array of challenges. Figure 7 offers a snapshot of key AM market opportunities as well as challenges; although not exhaustive, this list may serve as the basis for a more thorough examination of drivers and headwinds that may impact future developments in AM.

Figure 7. AM opportunities and challenges

OPPORTUNITIES

- Unprecedented design flexibility, allowing customization and new product development
- Consumerization/personalization of manufacturing
- Novel end-market applications in areas such as regenerative medicine
- Relocalization of US manufacturing
- Rapid product development and deployment
- Improving process sustainability (fewer yet greener materials; less energy and waste associated with production)

CHALLENGES

- Exuberance vs. natural evolution and true potential of the technology
- Ethical considerations (e.g., guns, bioprinting of human cells)
- Intellectual property/privacy issues
- Regulatory uncertainty in different countries
- Limited choice of materials
- Materials and process manufacturing qualification and certification standards
- Small production runs and scalability limitations

Sources: Deloitte analysis.

Graphic: Deloitte University Press | DUPress.com

The way forward

SOME believe that AM technology will continue to be used primarily for prototyping applications, due to its current inability to cost-effectively satisfy widespread manufacturing applications. Others believe that AM technology can revolutionize manufacturing processes. Regardless of one's viewpoint, there is little doubt that the past 30 years have witnessed an unceasing advancement in AM system functionality, ease of use, cost, and adoption across multiple industrial sectors. There exists an unmistakable shift in the AM landscape—from relatively common prototyping and modeling applications toward emerging applications aimed at manufacturing direct parts and end products.

If the past is prologue, the role that AM technology plays in the manufacturing value chain will grow in scope, scale, and complexity. While there is still some time before AM realizes its full potential, companies should assess how AM can help advance their performance, growth, and innovation goals.

Deloitte offers several detailed perspectives on specific aspects of the AM technology domain. Interested readers are directed to Deloitte's AM framework discussion in the article "3D opportunity: Additive manufacturing paths to performance, innovation, and growth," available on Deloitte University Press and to the Deloitte University Press collection on additive manufacturing at www.dupress.com/3D-Opportunity.[22]

Deloitte Consulting LLP's supply chain and manufacturing operations practice helps companies understand and address opportunities to apply advanced manufacturing technologies to impact their businesses' performance, innovation, and growth. Our insights into additive manufacturing allow us to help organizations reassess their people, process, technology, and innovation strategies in light of this emerging set of technologies. Contact the author for more information or read more about our alliance with 3D Systems and our 3D Printing Discovery Center on www.deloitte.com.

Endnotes

1. Mark Cotteleer and Jim Joyce, "3D opportunity: Additive manufacturing paths to performance, innovation, and growth," *Deloitte Review* 14, January 2014, http://dupress.com/articles/dr14-3d-opportunity/.
2. ASTM International, *Standard terminology for additive manufacturing technologies*, designation F2792 – 12a, 2013, p. 2.
3. The terms "additive manufacturing" and AM will be used throughout this report to refer to the technology set.
4. Laser Institute of America, *The history of laser additive manufacturing*, January/February 2012, p. 6.
5. T. Rowe Price Connections, *3D printing*, May 2012.
6. Ian Gibson, David W. Rosen, and Brent Stucker, *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing* (New York: Springer, 2009), p. 34.
7. The University of Texas at Austin, *Selective laser sintering, birth of an industry*," December 7, 2012, http://www.me.utexas.edu/news/2012/0712_sls_history.php, accessed January 25, 2014.
8. Gibson, Rosen, and Stucker, *Additive Manufacturing Technologies*, p. 34.
9. AM equipment providers are constantly introducing new systems at a variety of price points, including professional-grade and consumer models that occupy price points ranging from a few hundred to several hundred thousand dollars.
10. ASTM International, *Standard Terminology for Additive Manufacturing Technologies*. Designation: F2792 – 12a, 2013, p. 1.
11. We acknowledge the ongoing and rapid evolution of the AM technology marketplace. Our goal here is to provide an overview of the major process types used to fabricate full components in use at this writing. A variety of other process approaches may also be identified that, in particular, enable features to be additively created on traditionally manufactured components (e.g., direct write processes). For the purposes of this analysis, we adopt the seven major AM process types identified by ASTM.
12. A blue dot indicates that a given material is potentially used with a given technology. It does not indicate the extent of that material's use.
13. In addition to the categories of materials listed, powder bed and inkjet head 3D printing also uses sand molds.
14. In addition to the categories of materials listed, laminated object manufacturing also uses paper.
15. Wei Jun, Singapore Institute of Manufacturing Technology, *Opportunities and applications of 3D additive manufacturing*, April 11, 2013.
16. 3D Printing Industry, "The possibilities of nanoscale additive manufacturing," http://3dprintingindustry.com/2013/11/20/possibilities-nanoscale-additive-manufacturing/, accessed November 21, 2013; CSC, *3D printing and the future of manufacturing*, 2012.
17. For a detailed analysis of AM's implications in the aerospace and defense industry, refer to our report *3D opportunity in aerospace and defense: Additive manufacturing takes flight,* Deloitte University Press, June 2, 2014, http://dupress.com/articles/additive-manufacturing-3d-opportunity-in-aerospace/.
18. For a detailed analysis of AM's implications in the automotive industry, refer to our report *3D opportunity for the automotive industry: Additive manufacturing hits the road*, Deloitte University Press, May 19, 2014, http://dupress.com/articles/additive-manufacturing-3d-opportunity-in-automotive/.
19. For a detailed analysis of AM's implications in the medical technology industry, refer to our report *3D opportunity in medical technology: Additive manufacturing comes to life*, Deloitte University Press, April 28, 2014, http://dupress.com/articles/additive-manufacturing-3d-opportunity-in-medtech/.
20. "The National Additive Manufacturing Innovative Institute in Youngstown: What is it?," *The Plain Dealer*, February 12, 2013, http://www.cleveland.com/metro/index.ssf/2013/02/the_national_additive_manufact.html, accessed January 25, 2014.

21. "How 3D printing will make us self-sufficient," 2013, video on Forbes.com, 6:07, http://video.forbes.com/fvn/future-tech/autodesk-on-3d-printing, accessed January 25, 2014.
22. Cotteleer and Joyce, "3D opportunity."

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