Quadrennial Technology Review 2015

Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing

Technology Assessments

Additive Manufacturing

Advanced Materials Manufacturing

Advanced Sensors, Controls, Platforms and Modeling for Manufacturing

Combined Heat and Power Systems

Composite Materials

Critical Materials

Direct Thermal Energy Conversion Materials, Devices, and Systems

Materials for Harsh Service Conditions

Process Heating

Process Intensification

Roll-to-Roll Processing

Sustainable Manufacturing - Flow of Materials through Industry

Waste Heat Recovery Systems

Wide Bandgap Semiconductors for Power Electronics

U.S. DEPARTMENT OF ENERGY

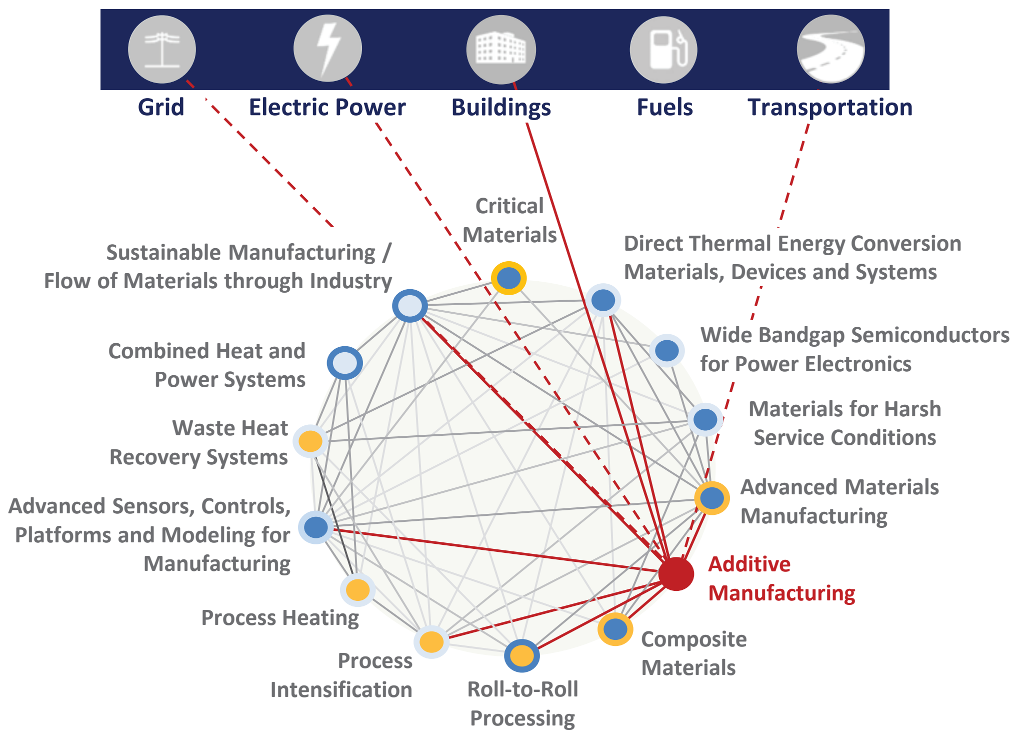
Quadrennial Technology Review 2015

Additive Manufacturing

Chapter 6: Technology Assessments

NOTE: This technology assessment is available as an appendix to the 2015 Quadrennial Technology Review (QTR). Additive Manufacturing is one of fourteen manufacturing-focused technology assessments prepared in support of Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing. For context within the 2015 QTR, key connections between this technology assessment, other QTR technology chapters, and other Chapter 6 technology assessments are illustrated below.[1]

Connections to other QTR Chapters and Technology Assessments



Representative Intra-Chapter Connections

- **Advanced Sensors, Controls, Platforms and Modeling for Manufacturing:** metrology and control systems for improved quality, defect detection, and throughput
- **Process Intensification:** microchannel reactor fabrication
- **Roll-to-Roll Manufacturing:** common technology needs for additive 2-D (roll-to-roll) and 3-D (additive manufacturing) printing technologies
- **Composite Materials:** 3-D printing of reinforced polymers and other composites
- **Advanced Materials Manufacturing:** material formulations for additive techniques
- **Direct Thermal Energy Conversion:** additive manufacturing of thermoelectric modules

Representative Extra-Chapter Connections

- **Fuels:** fuel cells
- **Electric Power:** custom electrical components in substations; complex parts for power plants; tooling for large castings for power plants
- **Buildings:** heat exchangers for HVAC systems; window frames
- **Transportation:** Prototyping and tooling in automotive applications; fuel cells

Introduction to the Technology/System

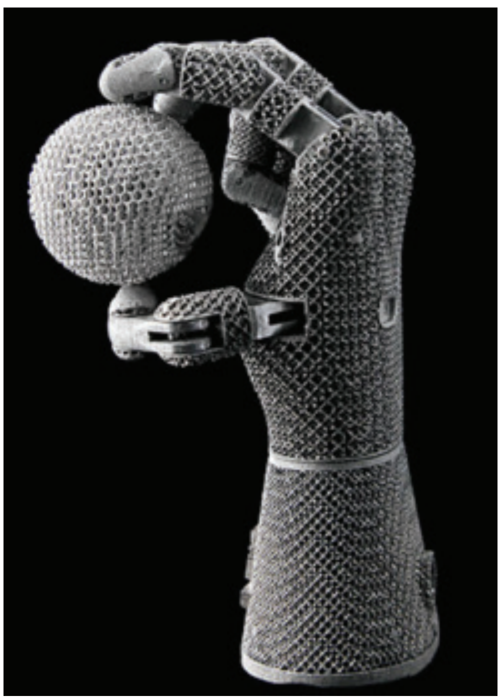
Introduction to Additive Manufacturing

Additive manufacturing (AM) is the process of producing objects from computer-aided design (CAD) model data, usually adding layer upon layer, in contrast to conventional subtractive manufacturing methods that involve the removal of material from a starting work piece.[2] AM is also called 3-D printing, additive fabrication, or free-form fabrication. These new techniques, while still evolving, are projected to exert a profound impact on manufacturing. They can give industry new design flexibility, reduce energy use, and shorten time to market.[3]

Interest in additive techniques has grown swiftly as applications have progressed from rapid prototyping to the production of end-use products. Additive equipment can now use metals, polymers, composites, or other materials to "print" a range of functional components, layer upon layer, including complex structures that may be difficult or impossible to manufacture by other means, such as the prosthetic hand shown in Figure 6.A.1.[4] It is also important to note that AM processes may not be applicable to all manufactured products produced using CM processes today. There are size, material property, and cost limitations that restrict its use (at least currently) to certain applications.

Figure 6.A.1 Titanium Prosthetic Hand Produced at Oak Ridge National Laboratory via Additive Manufacturing[3]

Credit: Oak Ridge National Laboratory



Additive Manufacturing Processes

Various AM processes have been introduced to the commercial market by industrial companies located in different countries (the United States, Germany, Sweden, the United Kingdom, Israel, etc.).[5] There are several systems to classify the AM processes, including one proposed by the American Society for Testing and Materials (ASTM) F42 Committee, which classifies the AM processes into seven areas as shown in Table 6.A.1.[6] The AM processes can also be classified based on the state of the starting material used (see Table 6.A.2).[4]

The ASTM F42 committee's standard terminology for AM technologies (ASTM F2792-12a[7]) was last updated in 2012, and there are emerging processes that may not necessarily fit into one of the current ASTM classifications. For example, a variant of the photopolymerization process is continuous liquid interface production (CLIP),[8] which utilizes an oxygen-permeable window below an ultraviolet image projection plane to create a liquid interface between the window and the polymerizing part. In this process, the solidified (polymerized) part is "pulled" from the liquid interface where the photopolymerization reaction takes place, allowing for the manufacture of parts with fine resolution without layer-to-layer interface issues typical of other 3-D printing processes that print layer by layer.

Table 6.A.1 The Seven AM Process Categories, as Classified by ASTM F42[6]

Process type	Brief description	Related technologies	Materials
Powder bed fusion	Thermal energy selectively fuses regions of a powder bed	Electron beam melting (EBM), selective laser sintering (SLS), selective heat sintering (SHS), and direct metal laser sintering (DMLS)	Metals, polymers
Directed energy deposition	Focused thermal energy is used to fuse materials by melting as the material is being deposited	Laser metal deposition (LMD)	Metals
Material extrusion	Material is selectively dispensed through a nozzle or orifice	Fused deposition modeling (FDM)	Various: typically polymer based
Vat photopolymerization	Liquid photopolymer in a vat is selectively cured by light-activated or UV polymerization.	Stereolithography (SLA), digital light processing (DLP)	Photopolymers
Binder jetting	A liquid bonding agent is selectively deposited to join powder materials, and then product is baked in an oven for final curing.	Powder bed and inkjet head (PBIH), plaster-based 3-D printing (PP)	Various: Polymers, sand, metals, other
Material jetting	Droplets of build material are selectively deposited	Multijet modeling (MJM)	Polymers, waxes
Sheet lamination	Sheets of material are bonded to form an object	Laminated object manufacturing (LOM), ultrasonic consolidation (UC)	Paper, metals

Table 6.A.2 Select AM Processes and Working Principles[4]

State of Starting Material	Process*	Material Preparation	Layer Creation Technique	Phase Change	Typical Materials	Applications
Liquid	SLA	Liquid Resin in a Vat	Light Scanning/ Light Projection	Photo-polymerization	UV Curable Resin, Ceramic Suspension	Prototypes, Casting Patterns, Soft Tooling
	MJM	Liquid Polymer in Jet	Ink-Jet Printing	Cooling & Photo-polymerization	UV Curable Acrylic Plastic, Wax	Prototypes, Casting Patterns
	RFP	Liquid Droplet in Nozzle	On-Demand Droplet Deposition	Solidification by Freezing	Water	Prototypes, Casting Patterns
Filament/ Paste	FDM	Filament Melted in Nozzle	Continuous Extrusion and Deposition	Solidification by Cooling	Thermoplastics, Waxes	Prototypes, Casting Patterns
	Robo-casting	Paste in Nozzle	Continuous Extrusion	-	Ceramic Paste	Functional Parts
	FEF	Paste in Nozzle	Continuous Extrusion	Solidification by Freezing	Ceramic Paste	Functional Parts

Key: SLA = stereolithography; **MJM** = multi-jet modeling; **RFP** = rapid freeze prototyping; **FDM** = fused deposition modeling; **FEF** = freeze-form extrusion fabrication; **SLS** = selective laser sintering; **SLM** = selective laser melting; **EBM** = electron beam melting; **LMD** = laser metal deposition; **3DP** = 3-D printing; **LOM** = laminated objective manufacturing

Table 6.A.2 Select AM Processes and Working Principles,[4] continued

State of Starting Material	Process*	Material Preparation	Layer Creation Technique	Phase Change	Typical Materials	Applications
Powder	SLS	Powder in Bed	Laser Scanning	Partial Melting	Thermoplastics, Waxes, Metal, Ceramic	Prototypes, Casting Patterns, Metal and Ceramic Preforms (to be sintered and infiltrated)
	SLM	Powder in Bed	Laser Scanning	Full Melting	Metal	Tooling, Functional Parts
	EBM	Powder in Bed	Electron Beam Scanning	Full Melting	Metal	Tooling, Functional Parts
	LMD	Powder Injection Through Nozzle	On-Demand Powder Injection and Melting by Laser	Full Melting	Metal	Tooling, Metal Part Repair, Functional Parts
	3DP	Powder in Bed	Drop-on-Demand Binder Printing	-	Polymer, Metal, Ceramic, Other Powders	Prototypes, Casting Shells, Tooling
Solid Sheet	LOM	Laser Cutting	Feeding and Binding of Sheets with Adhesives	-	Paper, Plastic, Metal	Prototypes, Casting Models

Key: SLA = stereolithography; **MJM** = multi-jet modeling; **RFP** = rapid freeze prototyping; **FDM** = fused deposition modeling; **FEF** = freeze-form extrusion fabrication; **SLS** = selective laser sintering; **SLM** = selective laser melting; **EBM** = electron beam melting; **LMD** = laser metal deposition; **3DP** = 3-D printing; **LOM** = laminated objective manufacturing

Benefits of Additive Manufacturing

AM and CM face different trade-offs, with each process likely to play a role in future manufacturing capabilities. AM has the potential to minimize materials and energy usage, reduce waste, accelerate innovation, and compress supply chains.[3] Listed below are some benefits of AM technology:

- **Innovation.** AM enables designs with novel geometries that would be difficult or impossible to achieve using CM processes. The novel designs enabled by AM can improve a component's engineering and cost performance and can also lead to performance and environmental benefits in a component's product application.[9] AM systems can also be programmed to tailor material properties within a component as desired to increase performance beyond that achievable through conventional processing.
- **Part consolidation.** The ability to design products with fewer, more complex parts rather than a large number of simpler parts may be the most important benefit of AM. This enables designs that are optimized for performance at a system level without making compromises for the sake of manufacturability at the subsystem level. Reducing the number of parts in an assembly may cut the overhead associated with documentation, production planning, and control. Also, fewer parts can mean that less time and labor is required to assemble the product, again contributing to a reduction in overall manufacturing costs. The "footprint" of the assembly line may also become smaller, further cutting costs.[3]
- **Lower energy consumption.** AM can save energy by eliminating production steps, using substantially less material, enabling reuse of by-products, and producing lighter products.[10]

- **Less waste.** Building objects up layer upon layer, instead of traditional machining processes that cut away material, can reduce material needs and costs by up to 90%.[5,11] AM can also reduce the "cradle-to-gate" environmental footprints of component manufacturing through avoidance of the tools, dies, and material scrap associated with CM processes. Additionally, AM could reduce waste by lowering human error in production.[12,13]
- **Reduced time to market.** Items can be fabricated as soon as the 3-D digital description (3-D scanning or 3-D imaging to construct a Standard Tessellation Language [STL] file) of the part has been created, eliminating the need for expensive and time-consuming part tooling and prototype fabrication.[10]
- **Lightweighting.** With the ability to create complex shapes, AM enables the design of parts that can often be made to the same functional specifications as conventional parts, but with less material. [3,13]
- **Agility of manufacturing operations.** AM enables rapid response to markets and creates new production options outside of factories, such as mobile units that can be placed near the source of local materials. Parts manufactured directly by AM do not need the (often) expensive tooling used in conventional operations, which must be amortized over long production runs, but the relatively slow production speed of AM is not currently effective for high volume production. In some cases, AM is used indirectly in the manufacturing operation to fabricate the molds, dies, and tooling used in the production process. Tooling can be designed, printed, and delivered to the shop floor faster and more cost effectively than by traditional methods, which are often outsourced. Spare tooling parts can be produced on demand, reducing or eliminating the need for stockpiles and complex supply chains.[10] However, the AM technologies required to manufacture metal tooling have relatively high capital costs and steep learning curves that need to be overcome to increase the rate of uptake by manufacturers.

Table 6.A.3 lists some common attributes of AM that distinguish it from CM and their impact on companies' existing product offerings and supply chains. Although not obvious, some product-related attributes impact commercial supply chains and vice versa. For example, while the manufacture of complex-design products

Table 6.A.3 Impact of AM Attributes on Product Offerings and Supply Chain Structures (e.g., Aerospace Industry)[14]

AM Attributes compared to traditional manufacturing	Impact on product offerings	Impact on supply chains
Manufacturing of complex-design products	Very High	High
New products that break existing design and manufacturing limitations	Very High	High
Customization to customer requirements	Very High	High
Ease and flexibility of design iteration	High	Medium
Part simplification/sub-parts reduction	Medium	Medium
Reduced time to market	Medium	Medium
Waste Minimization	Medium	Medium
Weight reduction	Medium	Low
Production near/at point of use	Medium	Very High
On-demand manufacturing	Low	Very High

Key: Very High, High, Medium, Low

is a product-aligned attribute, it also has supply-chain implications. Companies that are designing complex parts need to ensure fit and integration with other components sourced from suppliers. In a similar fashion, companies need to consider the impact of each AM attribute on their products and supply chain structures.[14]

Technology Assessment and Potential

Applications of Additive Manufacturing

The development of innovative, advanced AM techniques has progressed rapidly in recent years, and expanded to a broader range of industry applications.[4] Compared with conventional manufacturing, AM is particularly suitable for producing low volumes of products, especially for parts with complex geometries.[4] AM processes also offer great potential for customization, such as fabricating personalized implants for hip and knee replacements. The AM market in 2013, consisting of all AM products and services worldwide, grew 34.9% to approximately $3 billion, according to Wohlers' Report 2014. This compares to growth in 2012 of 32.7% to approximately $2.3 billion.[3] In the 2014 edition of the report, Wohlers Associates conducted a survey of 29 manufacturers of professional-grade, industrial AM systems (those that sell for $5,000 or more) and 82 service providers worldwide.[3] The survey asked each company to indicate which industries they serve and the approximate revenues (as a percentage) that they receive from each. Figure 6.A.2 shows the results. The "Other" category includes a wide range of industries, such as oil and gas, sporting goods, commercial marine products, and various other industries that do not fit into named categories.

Figure 6.A.2 Industries Served by AM Manufacturers and Service Providers[3]

Source: Wohlers Report 2014

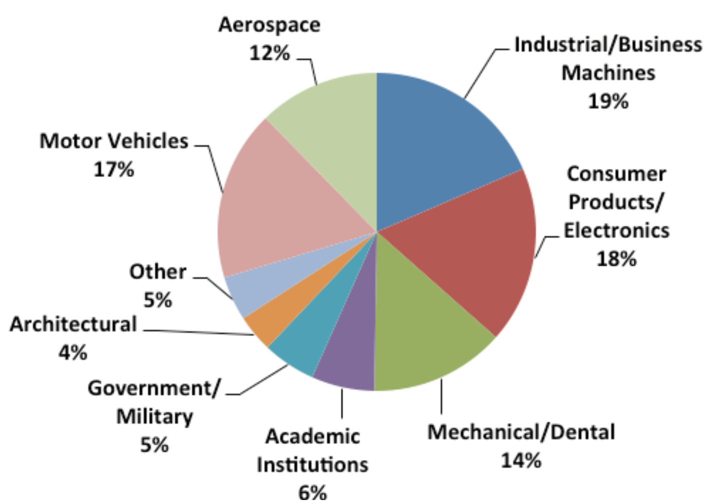


Figure 6.A.3 shows how organizations are using industrial AM systems for range of applications. The survey results show that companies use AM technology to produce functional parts more than anything else (29%).[3] The second most popular application for AM parts is prototypes for fit and assembly (19%).

An increasing number of industries benefit from advantages of AM technologies, such as increased freedom of design, and AM is progressively expanding from rapid prototyping towards small-series production. Today, AM is already widespread within certain known application areas, for instance within the aerospace and defense (A&D) industries, automotive and electronics industry, and the medical sectors.[15] Consumer industries (such as sporting goods, furniture, and jewelry) are also becoming aware of the advantages of AM technologies for their businesses. Table 6.A.4 illustrates the global opportunities arising for AM across many different industries,[16]

Figure 6.A.3 Consumer Uses of Parts Built on AM Systems[3]

Source: Wohlers Report 2014

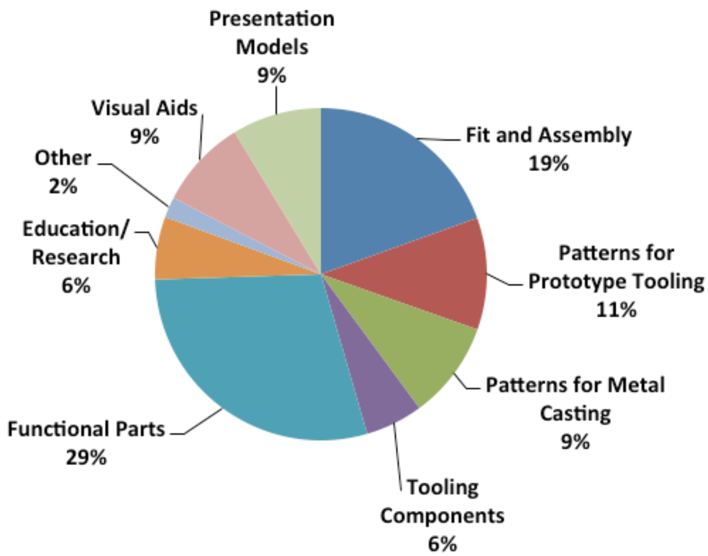


Table 6.A.4 Global Opportunities for AM Across Industries[16]

	Consumer	Small to mid-sized business	Corporations
In need of future R&D		■ Organ Replacement, $30B	■ Furniture, $20B ■ Consumer electronics, $289B
Nearing commercial use	■ US prepared food, $23B	■ Bicycles, $6B ■ Guns and ammo, $11B ■ Global Apparel, $1T	■ Life sciences R&D, $148B ■ Home building and improvement, $678B ■ Power tools, $22B
In use	■ Craft and hobby, $30B ■ Animation and gaming, $122B	■ Medical prosthetics, $17.5B ■ Retail hardware, $22B ■ US auto parts store, $40B ■ Toys, $80B	■ Industrial R&D (for prototyping), $23B ■ Aircraft and defense R&D, $9B

with current total market volume for different industries. However, the penetration of the industries by AM is still limited. To increase the penetration from today's point of view, the current, most relevant success factors across the analyzed industries include design rules, surface quality, process reliability, and part reproducibility.

The following subsections provide a brief review of AM applications in the A&D, automotive, electronics, tool and mold making, energy, building, and biomedical fields.

Aerospace & Defense (A&D) Applications

Today, about 12% of the overall AM market (AM products and services) is attributed to the aerospace industry, as shown in Figure 6.A.2,[3] which corresponds to approximately $380 million (U.S.).[3] Compared to the world market volume of the A&D industry (amounting to $706 billion in 2013[17]), the AM market share of the aerospace industry is still marginal, but use of AM is increasing.

Research and development (R&D) within the A&D industry is focused on continuously improving the efficiency of aircraft (including weight reduction) and reducing air and noise pollution.[18] These objectives require parts that are lightweight, strong, and electrically conductive in some cases.[19] In addition, most products are geometrically complex and manufactured in small quantities with high unit costs. Owing to these special characteristics, the A&D industry is particularly suitable for early adoption of AM, and AM technologies have already begun penetrating this market.[19] For instance, Boeing and Airbus are already using AM technologies to reduce production time, build lighter-weight parts, and reduce operational costs. In addition, a number of smaller companies within the aerospace supply chain have begun to deploy AM. AM has contributed to reducing or even eliminating tooling, welding, inventory, and entire assembly lines.[20] Current and potential applications within the aerospace industry are shown in Table 6.A.5.

Table 6.A.5 AM Applications in the Aerospace Industry[14,21]

	Current Applications	Potential Applications
Commercial Aerospace and Defense	■ Concepts modeling and prototyping ■ Printing low-volume complex aerospace parts ■ Printing replacement parts	■ Embedding AM electronics directly on parts ■ Printing aircraft wings ■ Printing complex engine parts ■ Printing repair parts on the battlefield
Space	■ Printing specialized parts for space applications ■ Printing structures using lightweight, high-strength materials ■ Printing parts with minimal waste	■ Printing on-demand parts/replacements in space ■ Printing large structures directly in space, thus circumventing launch vehicles' size limitations

The design and manufacturing of lighter-weight parts plays a particularly important role for the aerospace industry. For instance, the following parts have already been manufactured using additive technologies:

- Structural parts for unmanned aircraft by Saab Avitronics[22,23]
- Specialized assembly tools[24]
- Customized interiors of business jets and helicopters[22]
- Physical 3-D mock-ups by Boeing[22]
- Turbine blades[20]—for example, General Electric (GE) engineers are starting to explore the manufacture of multimaterial blades so that one end is optimized for strength and the other for heat resistance[25]
- Windshield defrosters by AdvaTech Manufacturing[19]
- Fuel nozzles for gas turbine applications by GE[26,27]
- Engineered thermoplastic air ducts by Structural Integrity Engineering, Inc.[28]

In addition, AM technologies are used for repair and remanufacture of worn component parts, such as turbine blade tips and engine seal sections (e.g., by Rolls Royce).[29] GE has produced 40,000 to 80,000 new-make high-pressure turbine blade tips per year by using additive technologies since 1990. GE also has been using AM to repair over 200,000 compressor blades and high-pressure turbine blades annually since the mid-1990s.[30]

Other trends identified to be relevant for the A&D industry are as follows:

- Increasing usage of lightweight structures
- Implementation of innovative and ergonomic features in designs for adding strength to components

- Embedding AM electronics directly on parts[14]
- Increasing individualization of design and customization of the interior of aircraft
- Intensified research in terms of developing new materials and differentiation features (e.g., individual cabin layout)
- Application of AM technologies for tooling and fixturing
- Adaptive shapes, especially adaptive wings

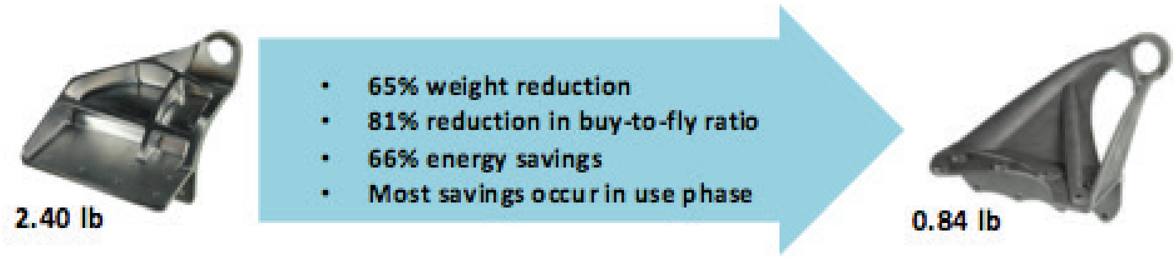
Table 6.A.6 provides an example of how AM enables weight reduction by optimizing design structure.

Table 6.A.6 AM Enables Weight Reduction by Optimizing Design Structure[31,32]

Traditional Design	AM Optimized Design
	
■ A conventional steel buckle weights 0.34 lb (or 0.26 lb when made of aluminum)	
■ Titanium buckle designed with AM weighs 0.15 lb—a reduction of 55%	
■ For an Airbus 380 with all economy seating (853 seats), this would mean a reduction of 160 lbs	
■ Over the airplane's lifetime (30 years), 872,000 US gallons of fuel or approximately $2.3 million could be saved, assuming a saving of 5,390 gallons per lb-mile eliminated and a 30 year airplane lifetime for short haul aircraft[32]	
■ Development partners are Plunkett Associates, Crucible Industrial Design, EOS, 3T PRD, Simpleware, Delcam, University of Exeter	

Another example that shows how aerospace components manufactured by AM processes have an energy impact for many years after they leave the factory is illustrated in Table 6.A.7. Weight reduction is particularly relevant for aerospace components that have long service life and where mass reductions can lead to cost-effective energy savings. The part shown in Table 6.A.7 is an aerospace bracket used in aircrafts to affix structures, such as those in kitchens, lavatories, and galleys. This bracket is typically produced by conventional milling and machining processes with a very high buy-to-fly ratio (8:1). A similar bracket (a bracket with the same functionality but with a topologically optimized geometry) can be produced by an electron-beam melting process with a significantly lower buy-to-fly ratio (1.5:1). The optimized design results in a bracket that is 65% lighter, saving manufacturing materials and resulting in use-phase energy savings.[13] Table 6.A.7 also shows that AM could also reduce energy consumption in the freight and distribution phase. In the case of freight and distribution, energy use is a function of how far the component part has traveled within the supply chain, the weight of the part as it moved through the supply chain, and the modes of transport used to move the part within the supply chain.

Table 6.A.7 Life-Cycle Energy Savings for a Titanium Aerospace Bracket[13]



Life Cycle Phases	Unit	Conventional Manufacturing*	Additive Manufacturing*	Energy Savings per Part*
Material Energy	Btu/part	2,020,000	264,000	1,760,000
Manufacturing Energy	Btu/part	65,500	65,900	(400)
Freight and Distribution Energy	Btu/part	40,500	14,200	26,300
Use Phase Energy	Btu/part	99,600,000	34,900,000	64,700,000
Disposal (End of Life) Energy Use	Btu/part	(434,000)	(152,000)	(282,000)
Total Energy Use per Part	**Btu/part**	**101,000,000**	**35,000,000**	**66,000,000**

*Numbers are rounded to the nearest 100 Btu/part. Parentheses indicate negative values.

Automotive Applications

The automotive industry is already a major user of rapid prototyping equipment: AM technologies are being applied to functional prototypes and for small and complex parts for luxury and antique cars.[15] The automotive industry has been using AM technology as an important tool in the design and development of automotive components because it can shorten the development cycle and reduce manufacturing and product costs.[4] The motor sport sector constitutes an important field for the application of AM technologies because in this sector high performance and low weight play a central role.[15] Within the automotive industry, increasing competition reinforces the pressure for reducing the time to market. This challenges the automotive industry to secure and further expand the market share of advanced manufacturing technologies, including AM technologies.

In 2013, the automotive industry contributed 17.3% to the total AM market volume (Figure 6.A.2).[3] This corresponds to approximately $530 million (U.S.). Thus, the automotive industry is one of the major users of AM.[3] However, the AM market is still marginal compared to the world market volume of the automotive industry, which amounted to $2 trillion in 2013.[33]

AM is already widespread within the automotive industry and is being used for a great variety of applications (such as concept modeling, functional testing, rapid manufacturing, and production planning) across the automotive industry.[34] However, AM is currently only used for prototyping and direct manufacturing of small, complex, and non-safety-relevant components within small series because process reliability and consistency of products is still limited.[20] The build envelope plays a central role because many parts are too large to be manufactured in most currently available AM machines. Note that new processes that are extending the boundaries of the build envelope are emerging (see the case study at the end of this technology assessment on Big Area Additive Manufacturing [BAAM]).

Some examples of notable applications are named in the following:

- Testing part design to verify correctness and completeness of parts by BMW, Caterpillar, Mitsubishi[15,19,35]
- Parts for racing vehicles (e.g., aerodynamic skins, cooling ducts, electrical boxes)[22,24,36,37]
- Prototype or pre-series components for luxury sport cars (e.g., intake manifolds and cylinder heads by Lamborghini)[34,35]
- Replacement of series parts that are defective and/or unavailable (e.g., cover flaps by Lamborghini)[35]
- Assembly assists for series production by BMW and Jaguar[19]
- Concept models and functional prototypes of Ducati engines (e.g., engine designed for its Desmosedici race bike) by Stratasys, Ltd[38]

The automotive industry is expected to generate a large demand for AM-produced equipment (see Figure 6.A.4 for examples of current and future applications).[15,33] Further trends within the automotive industry are as follows:

- Higher demand for lightweight structures[23]
- Increasing demand of replacement parts for antique cars[36]
- Increasing worldwide desire for individual mobility[18]
- Electrification of the power train[18]
- Higher focus on sustainable mobility[18]
- Increasing importance of individual customer needs[18]
- Higher density of traffic[18]

Automobiles also provide a good platform to test emerging AM processes in coordination with a range of next generation vehicle technologies. Figure 6.A.5 shows a 3-D printed Shelby Cobra replica, a test-bed of next generation vehicle concepts based on a classic American car design. Researchers printed the Shelby Cobra at U.S. DOE's Manufacturing Demonstration Facility (MDF) at ORNL using the BAAM process, which can manufacture strong, lightweight composite parts without the need for tooling.[39] Out of 1,900 lbs total vehicle weight, 500 lbs of parts are printed via BAAM using a composite polymer material (80% ABS and 20% carbon fiber). The new BAAM system, which was jointly developed by ORNL and Cincinnati Incorporated, is 500 to 1000 times faster and capable of printing polymer components 10 times larger than today's industrial additive machines—in sizes greater than one cubic meter. This project also showed that AM enables the seamless integration of advanced technologies with design flexibility and modularity while providing a platform for rapid development and evaluation. The printed car incorporates "plug and play" components such as new engine, battery, and fuel cell technologies; hybrid system designs; and power electronics and wireless charging systems, allowing researchers to easily and quickly test innovative ideas in a driving laboratory.

Figure 6.A.6 shows an example of a Delphi diesel pump housing manufactured by using the selective laser melting (SLM) process. Delphi is a tier 1 automotive supplier, and currently uses SLM instead of traditional machining of aluminum die castings to make diesel pumps. The SLM process allowed Delphi to make the pump as a single piece, while also avoiding a number of subsequent operations such as drilling, machining and chemical deburring, which reduced overall production costs and yielded a final product that is less prone to leakage.[33,40] The conventional gravity casting and machining process to make the pump housing required a

Figure 6.A.4 Illustrative Diagram Showing Automotive Applications of AM[33]

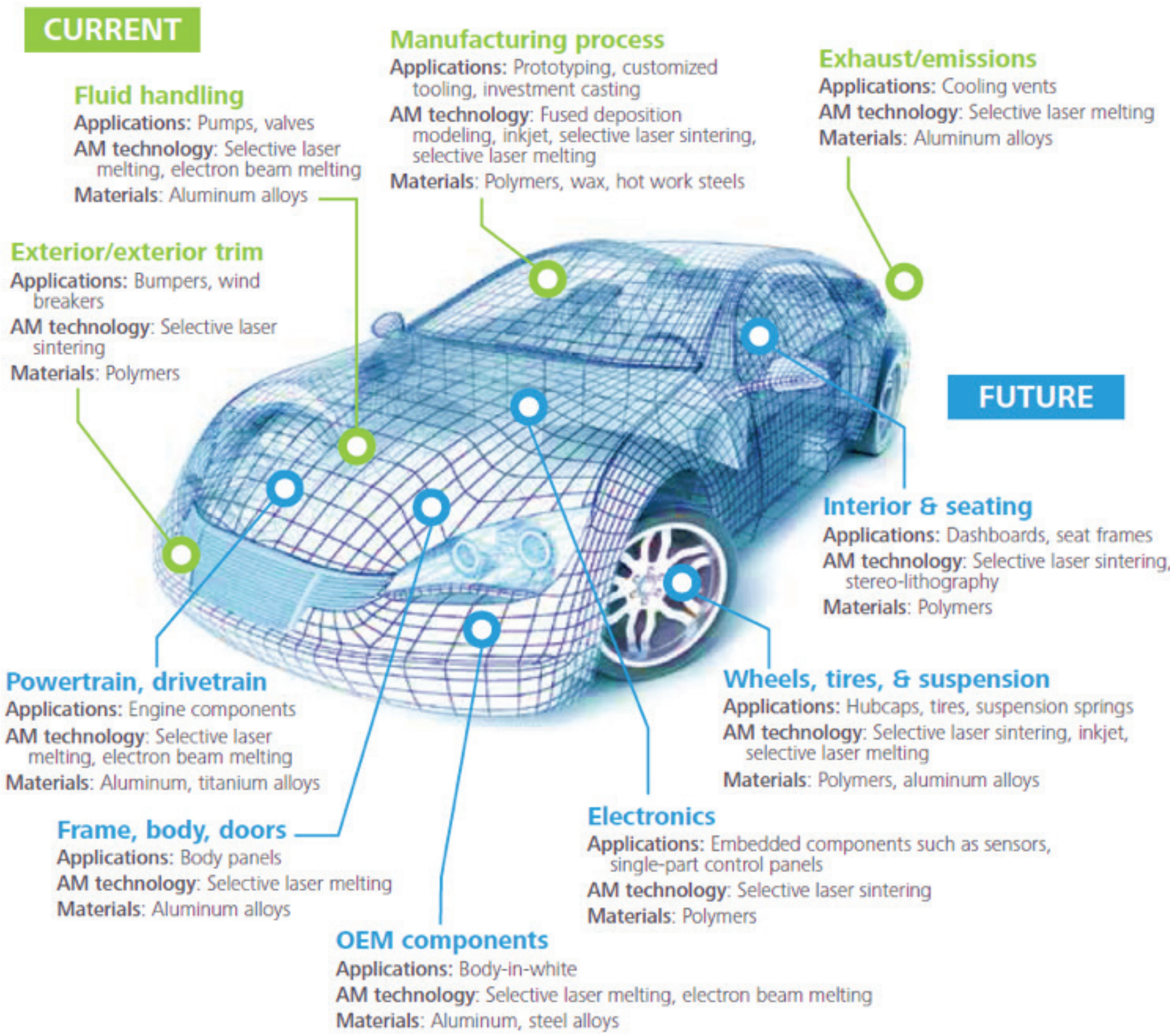


Figure 6.A.5 3-D Printed Shelby Cobra Replica. See http://web.ornl.gov/sci/manufacturing/shelby/ for links to videos of the printing process.

Credit: Oak Ridge National Laboratory

buy-to-fly ratio of 2:1. The same housing with same geometry can be produced with the SLM process, with a significantly lower buy-to-fly ratio (1.4:1).[40] Table 6.A.8 compares the life-cycle energy consumption of a conventional production system with that of an SLM AM process for aluminum as well as a stainless steel housing. The energy savings are primarily the result of the reduced material consumption enabled by the additive process and use phase savings from the lighter final part weight.

Figure 6.A.6 Delphi Diesel Engine Pump Housing Produced by selective laser melting[40]

Credit: Delphi Automotive

Electronics Industry Applications

Electronics industry applications range from mobile phones and computers to cars.[15] Technological advance is rapid and lifetimes of electronics are often short. Electronics products are often small and require high-precision tools for the manufacturing processes, and new manufacturing equipment is needed frequently. AM technologies can enable manufacturing equipment to meet the challenge of the rapid technological advancements required for new products.[34]

Table 6.A.8 Mass and Energy Use Comparison for Automotive Diesel Engine Pump Housing (Delphi) Manufactured by Various Pathways and Materials[40]

Manufacturing Pathway	Gravity die casting – Aluminum	Selective Laser Melting – Aluminum	Selective Laser Melting – Stainless Steel 316L
Material input	4.4 lbs	0.7 lbs	2.0 lbs
Final part mass	2.3 lbs	0.5 lbs	1.3 lbs
Life cycle stage			
Raw materials	305 kBtu	64 kBtu	68 kBtu
Manufacture	5 kBtu	28 kBtu	87 kBtu
Transportation	45 kBtu	7 kBtu	15 kBtu
Use phase	324 kBtu	73 kBtu	209 kBtu
End of life*	1 kBtu	0 kBtu	0 kBtu
TOTAL	**681 kBtu**	**173 kBtu**	**379 kBtu**

*As final part mass in SLM (Al) and SLM (SS 316L) is significantly less, end of life energy use per engine pump is negligible.

Against this background, the integration of functions into structures is gaining importance. AM technologies are suitable to meet these requirements through embedding electronic circuits into various geometries.[15]

The application potential for AM technologies has been increasing in electronics production, as new polymer and metal-based materials and inks have been reaching the market. AM is already used for products such as the following:[15]

- Embedding radio frequency identification (RFID) devices inside solid metallic objects
- Polymer-based, three-dimensional micro-electromechanical systems(MEMS);
- Microwave circuits fabricated on paper substrates
- All kinds of grippers within automated production systems

The total world market volume for electronics amounted to $5 trillion in 2013.[41] In 2013, the consumer electronics industry contributed 18% to the total AM market volume.[3] This corresponds to approximately $553 million.[3]

Trends identified for the electronics industry are as follows:[15]

- Growing demand for accelerated product development, requiring shorter lead times for tooling
- Focus on integration and services
- Increasing demand for embedded electronics
- Miniaturization and functional integration of devices
- Growing demand for smart microsystems
- Emerging market for polymer electronics

Tool and Mold Industry

Tooling includes molds, dies, and fixtures. Tooling ranges from early-stage prototypes to full-scale production and is a capital and knowledge-intensive industry.[23] Aeronautics, automotive vehicles, electronics, and household equipment goods are some products where tooling is an important part of the design and manufacturing process. Tooling is crucial for the competitiveness, efficiency, and robustness of a production system because it links final parts (products and components) and production equipment (machine tools).[23]

Today, the development and manufacture of tooling can be one of the most expensive and time-consuming steps within many manufacturing processes. This is mainly due to complex geometries of final parts that require high accuracy and reliability, low surface roughness, and strong mechanical properties.[34,42] Furthermore, tooling strongly depends on its intended application because different applications require different materials, part volume, size, etc.[23]

AM has the potential to contribute in different ways within the tooling industry: on the one hand, AM can be applied for the production of tooling; on the other hand, the use of AM in manufacturing can function as a tooling substitute. Both deployment possibilities can provide numerous advantages over CM technologies. A study conducted by Northwestern University presents an integrated techno-economic model to estimate product lead-time, life-cycle primary energy use, greenhouse gas (GHG) emissions, and costs of a typical injection mold for comparison of distributed AM over CM.[43] Their life-cycle inventory (LCI) results demonstrated a savings of about 50% in mold lead time, 40% in primary energy and GHG emissions as well as a 30% cost savings for the distributed additive manufactured mold, assuming a 1-million-cycle lifetime (Figure 6.A.7).[43]

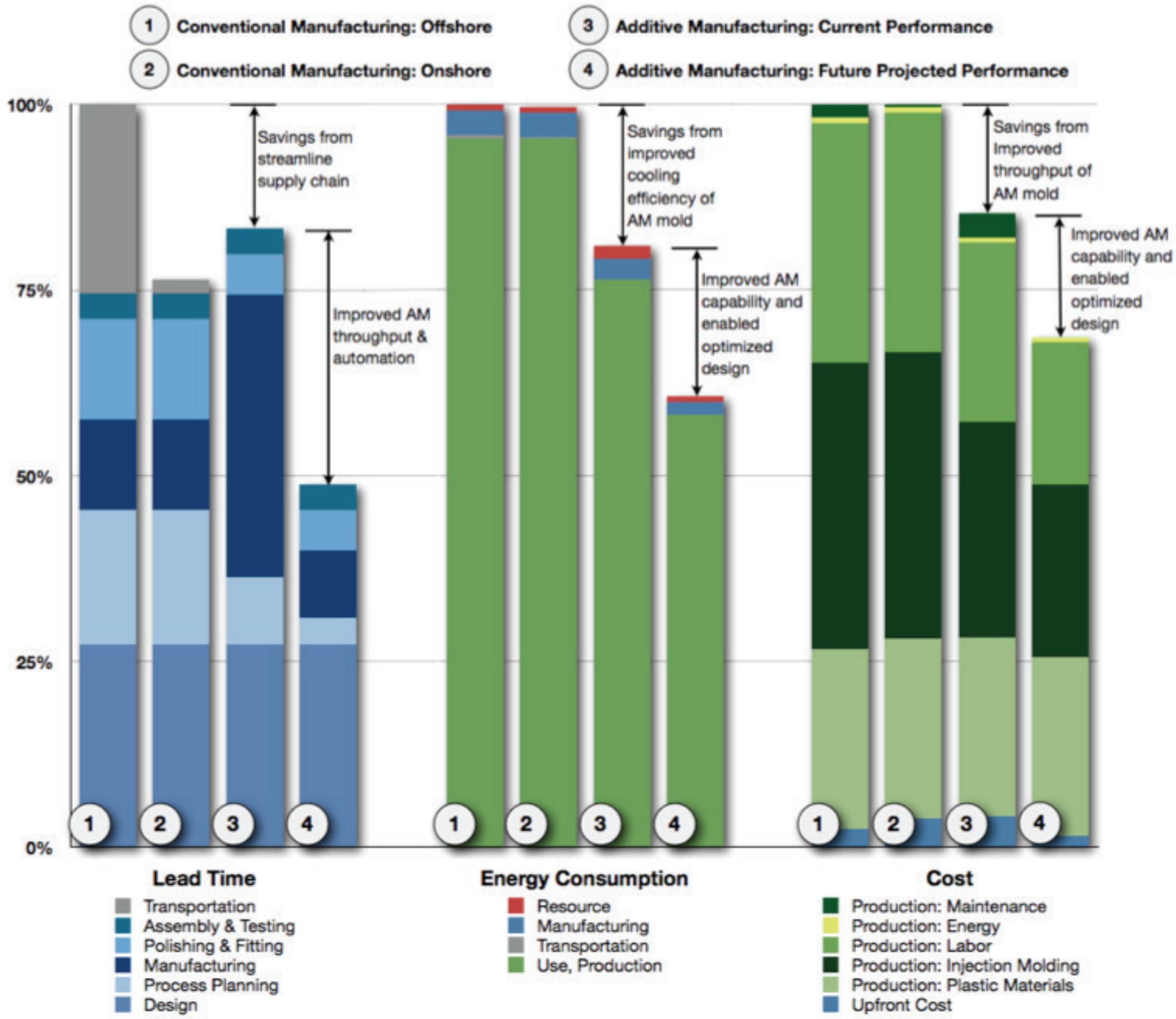
AM can streamline and improve manufacturing processes, for instance in the production of cooling channels within the tooling. Using traditional methods, the channels need to be drilled into the tooling. Owing to the notch effect, this process creates stress concentrations. This negative effect can be counteracted by AM because AM technologies can produce tooling with integrated cooling channels by a single process, at lower costs, and within a shorter time.[15] Thereby, the time to market can be reduced, and the product development cycle can be shortened.[15,34]

The U.S. tool, die, and industrial mold industry comprises approximately 6,300 small- and medium-sized businesses that manufacture highly customized products for use with machine tools and other types of production machinery.[44] The AM tooling market includes tooling produced from AM patterns and AM systems as well as molded parts and castings. In 2013, the total volume was approximately $798 million (U.S.) (around 26% of the total AM market [see Figure 6.A.3]). Compared to the primary market volume, the AM market volume of the tooling industry is considerable.[45]

Despite serious competition within the tooling industry regarding conventional technologies, AM is already widespread within the tooling industry as reflected by the positive market development.[15] Ironically, AM technologies compete with one another in this field of application because AM of final products actually lowers the demand for tooling in small series production.[15] An example for direct tooling is the fused-deposition modeling (FDM) process. Owing to improved variety and durability of AM material, FDM can be applied to produce parts that require strength and durability. The following list includes additional applications in industry:

- Universal tool holders with standardized casting insert pocket sizes[15,22]
- Die casting forms[15]
- Injection molding tooling[34]
- Patterns for investment casting[45]
- Fixtures for tooling[23]
- Tooling for prototyping of surgical devices[15]

Figure 6.A.7 Lead Time, Energy Consumption and Cost Implications of the Distributed Additive Manufacturing Mold With a 1-Million-Cycle Lifetime[43]



While these industries represents a significant opportunity, conventional technologies and current practices are barriers to the expanded uptake of AM technologies, which can be capital intensive and difficult for many small and medium size enterprises to adopt. Further RD&D is needed to develop some of the capabilities that will enable the full range of AM benefits to be cost-effectively realized by a greater cross-section of manufacturers. Use of AM can enable a considerably shorter development and manufacturing process. The use of parallel production can improve efficiencies and speeds of the production process, reducing energy use. AM-enabled rapid production can also lower manufacturing costs,[46,47] allowing investments to pay off within a relatively short period. AM technologies used in the manufacturing of die-casting models can enable rapid creation of complex geometries and shapes with a minimum of manual work.[45] Thereby, production times can be reduced and the quality of parts produced increased. The replacement and maintenance of tooling becomes easier, faster, and more cost-effective, especially as spare parts can be produced just-in-time.

However, there are indications that the development of AM has been stagnating within the tooling industry, and less research on tooling applications has taken place within recent years.[46] The following trends have been identified for the tooling industry:[15]

- The demand for accelerated product development requires shorter lead times of tooling.
- Efforts are made to reduce the break-even time of tooling.
- Increasingly shorter life cycles of tooling are required to increase production of low-volume niche products.
- The deployment of universal tool holders and higher use of multicomponent techniques while manufacturing small parts are increasing.

Energy Applications

As a widely applicable process technology, AM will impact energy in many different sectors, as discussed in the preceding sections. AM may also contribute to energy efficiency across sectors, whether through the rapid development and fabrication of prototypes to reduce the cost and lead time of new products or more directly through the production of energy-saving products, such as compact, high-surface area heat exchangers, that are more efficient than heat exchangers made by conventional methods.

Within the energy sector, AM is being explored for a range of applications spanning energy production, storage, and delivery. For example, selective laser sintering (SLS) based processes have been used to fabricate graphite composite bipolar plates, which is one of the most important components in polymer electrolyte membrane (PEM) fuel cells.[48,49] By using SLS, the cost and lead-time to develop new bipolar plates can be reduced dramatically compared with conventional methods, such as injection molding and compression molding, in which expensive metal molds must be manufactured. AM applications in electricity production include turbine blades for windmills, custom electrical components used in substations, high-temperature alloys for combustion and steam turbines, tooling for large castings, radiation-tolerant materials for nuclear applications, high-toughness materials for heat engines, and other complex parts used in power plants.

Building Sector Applications

Prefabricated green homes can save considerable energy and carbon emissions over the average site-built home, but they are often shipped over long distances, increasing the energy and carbon footprint of even the most environmentally friendly materials. AM processes have the potential to address this problem. For example the ORNL partnered with Clayton Homes and Skidmore, Owings & Merrill (SOM) on a project to 3-D print an energy-efficient home, the Additive Manufacturing Integrated Energy (AMIE) Demonstration Project.[50] This project also demonstrates approaches to break down barriers to improved energy integration and utilization between the buildings and transport sectors by wirelessly sharing energy between the 3-D printed car and house (see Figure 6.A.8). Both the home and car are printed out of a CFRP material. Another example is DUS Architects's (a Dutch firm) 3-D printed Canal House.[51] DUS Architects is aiming to use AM to construct components of a complete house on site, using equipment housed in a shipping container, and working through the house room-by-room.[52] The project started in 2014 and will end most likely in 2017. This effort investigates the opportunities for AM to impact architecture, and will expand the design and production pathways for sustainable housing. AM would help reduce the cost of transporting materials and cut down on the waste, and buildings constructed by AM techniques could be dismantled and moved in units or completely recycled.[53]

Buildings require many complex parts (e.g., joist connectors, framing, joints to windows and doors, and facades), and new geometries are being explored in part formation that would enable weight savings and

Figure 6.A.8 The Additive Manufacturing Integrated Energy (AMIE) Demonstration project at ORNL is exploring the potential for AM to expand the design opportunities for improved energy utilization between the buildings and transport sectors.[55]

Credit: Oak Ridge National Laboratory

simplify structures beyond what is currently available. For example, a recent dissertation at Delft University of Technology demonstrated the potential of additive methods for the development of facade construction.[54] The benefits that make the use of AM technologies such as lightweight construction, free form, material savings, and integral functionality, could vitiate traditional design strategies.

Biomedical Applications

AM technologies enable production of items that are tailored to a patient's unique requirements. Research opportunities of AM technology in the biomedical field include the following:

- Creating design and modeling methods for customized implants and medical devices
- Developing viable bio-AM (BAM) processes for fabrication of "smart scaffolds" and for construction of 3-D biological and tissue models using living biologics
- Creating computer-aided BAM, including modeling, analysis, and simulation of cell responses
- Making functional human tissues by using 3-D "bio printing" technology"[52] (for example, the medical research company Organovo has achieved excellent function in a fully cellular 3-D human liver tissue and their 3-D "bio printing" technology was selected as one of the "Best Inventions of 2010" by TIME® magazine[52]

In 2012, the market volume of the biomedical industry (implants and prosthetics) amounted to $121.6 billion.[56] Regarding the AM market, the medical and dental industries have a market share of approximately 13.7%, corresponding to approximately $420 million.[3]

Challenges for Additive Manufacturing

To achieve a wider range of applications for AM, R&D efforts will need to overcome some key technical challenges, including the following:

- **Process control.** Feedback control systems and metrics are needed to improve the precision and reliability of the manufacturing process and to increase throughput while maintaining consistent quality.[57] Feedback control is especially challenging for AM processes, with rapid deposition rates. The ability to tailor the material microstructure in situ could improve performance properties.
- **Tolerances.** Some potential applications would require micron-scale accuracy in printing.[18]
- **Finish.** The surface finishes of products manufactured with additive technology require further refinement. With improved geometric accuracy, finishes may impart improved tribological and aesthetic properties.
- **Scalability.** CM processes (e.g., injection molding and casting) are mature and suitable for large-volume production. AM products are currently not performing at the same scales.
- **Processing speed.** While low-volume production is faster than CM, higher volumes are considerably slower. For example, a new generation of AM machines is needed to replace injection molding and casting machines. Making parts in parallel production (side-by-side in the machine) may speed up the process, allowing AM to compete with CM methods such as injection molding.
- **Electrical power.** The impact of power quality on AM equipment is not well understood. Power variations and interrupts can impact the quality of the item produced using AM by introducing defects that may not be detected. Research is needed to evaluate the power quality characteristics of AM equipment and develop a better understanding of the design and makeup of this new type of manufacturing system.
- **Material compatibility.** Materials that can be used with AM technologies are currently limited to a relatively small set of compatible materials. There is a need for new polymer and metal materials formulated for AM to provide materials properties, such as flexibility, conductivity, transparency, safety, and low embodied energy.
- **Validation and demonstration.** Manufacturers, standards organizations, and others maintain high standards for critical structural materials, such as those used in aerospace applications. Providing a high level of confidence in the structural integrity of components built with additive technology may require extensive testing, demonstration, and data collection.[18] The cost to establish material properties for each material, to each additive process, and to a lesser extent each machine, can exceed many thousands of dollars (and millions in critical applications)—a huge barrier to entry.
- **Modeling.** Modeling and simulation of AM enables the design and implementation of process control methods. Physics-based process models are needed to understand the fundamental physics of AM processes, both for current single material processes and especially for multi-material additive processes, where interface issues, such as bonding and thermal expansion, can present significant issues. For example, numerical modeling of the solidification of metal alloys is very challenging because a general solidification of metal alloys involves a so-called "mushy region" over which both solid and liquid coexist and the transport phenomena occur across a wide range of time and length scales.

In addition to technological challenges, AM processes also face an array of business- and market-level challenges. For example, industry designers are familiar with CM methods, and parts are often designed based on CM processes. Widespread adoption of AM will require education, training, and approaches to mitigate business risks associated with the transition to a rapidly advancing technology. Table 6.A.9 offers a snapshot of key AM market opportunities as well as challenges.

Table 6.A.9 AM opportunities and challenges[14]

Opportunities	Challenges
■ 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 U.S. manufacturing ■ Rapid product development and deployment ■ Improving process sustainability (fewer yet greener materials; less energy and waste associated with production)	■ 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

Research and Development in Additive Manufacturing

AM continues to be a hot topic for research, driven by organizations such as the National Additive Manufacturing Innovation Institute (also called America Makes), the Manufacturing Demonstration Facility at ORNL, and the National Science Foundation (NSF).

The following list covers the overall objectives of current R&D efforts in AM:[3]

- **Freedom of design for the manufacturing parts.** Efforts are ongoing to produce mesoscale features, such as cellular structures, optimal designs, and textiles, with repeated unit cells using AM. A line of research dealing with microscale part production is also developing.
- **Scalability.** AM systems are being built that are not limited by the usual operational envelope in which parts are made and are capable of building metal or polymer parts outside of a controlled (heat and atmospheric) environment. AM systems that are suitable for large-volume production are also needed.
- **Processing speed.** AM machines are being developed with higher throughput in order to enable new markets and facilitate parallel production (side-by-side in the machine) to speed up the process, allowing AM to compete with CM methods.
- **Sustainability.** Energy consumption, water use, and waste production are being studied to identify approaches that significantly improve sustainability, particularly compared to CM.
- **Supply chain management and logistics.** Many studies and reports currently underway look at AM from the context of the ongoing changes it is causing in the manufacturing industry and society in general. The effects of a disaggregated supply chain on the delivery of products and services and the location and nature of jobs associated with those effects are examples that are becoming increasingly prevalent.
- **Qualification, validation, and verification of AM parts.** The increased need for qualification, validation, and verification of AM parts is associated with the growing numbers of AM parts being used in service applications, particularly in the safety-critical areas of aerospace and biomedical. In many cases, existing tests (e.g., stress and failure) need to be recalibrated to accommodate AM-manufactured parts, but standards organizations and regulating bodies have not yet determined what the correct qualification procedures should be in many cases.

The 2009 report, "Roadmap for Additive Manufacturing: Identifying the Future of Freeform Processing," produced from an NSF workshop,[20] contains a detailed discussion of AM research needs in the future. The pervasive topics for AM research covered in the 2009 report for AM[20] are briefly described in the sections below.

Design

The unique capabilities of AM (e.g., ability to fabricate complex shapes, tailor materials and properties, and handle functional complexities) open up design options that were previously unobtainable. For example, AM can provide the ability to manufacture embedded features (such as internal, helical cooling channels on engine components) or the ability to design complex geometries or properties that address specific performance requirements. However, it is not easy for designers to take advantage of these capabilities. Industry has yet to improve design to the point where it covers the full range of resources that manufacturing facilities require. To address this issue, the following developments are needed.[3,4,20]

- Conceptual design methods to aid designers in defining and exploring design spaces enabled by AM, methods for simultaneous product–process design and multifunctional design, and methods by which to assess life-cycle costs and impacts of parts and products fabricated by AM.
- A new foundation for CAD systems to overcome the limitations of existing solid modeling in representing complex geometries and multiple-material systems.
- Simulation capabilities for primitive shapes, materials, material compositions, etc.; multi-scale modeling and inverse design methodologies to assist in navigating complex process-structure-property relationships; and improved finite element analysis software that can make use of such capabilities.
- Methods to model and design with variability: shape, properties, process, etc.

Process Modeling and Control

In any manufacturing process, the ability to achieve predictable and repeatable operations is critical. It is important to reduce process variability and the sensitivity to process variations. To achieve this, research in the following areas is needed:

- Predictive process-structure-property relationships integrated with CAD, computer-aided engineering, and computer-aided manufacturing tools.[3,4,20]
- Closed-loop and adaptive control systems with feed-forward and feedback capabilities; control system algorithms must be based on predictive models of system response to process changes.[3,4,20]
- New sensors (process, shape/precision/surface finish) that can operate in build chamber environments and in sensor fusion configurations.[3,4,20]
- Modeling systems that combine design and manufacturing; the ability to predict manufacturing outcomes, decreasing defects and increasing part quality.[57]
- Rapid characterization tools, including product quality and material characterization; in-process process sensing, monitoring, and model-based optimal control; and performance qualification of materials, processes, and parts.

Materials, Processes and Machines

Research opportunities in AM materials, processes, and machines include the following:[3,4,20,22,57,58]

- Improving understanding of the basic physics of AM processes to capture the complexity in the multiple interacting physical phenomena, requiring new in situ characterization and testing capabilities.

- Developing processes based on scalable and fast material processing methods, such as processes that can fabricate a line (e.g., ink-jet printing) or area (e.g., mask-projection) to greatly increase machine throughput.
- Creating new, open-architecture controllers for AM machines and the development of reconfigurable, standard machine modules that could impact the AM field.
- Leveraging unique AM characteristics to produce epitaxial metallic structures, fabricate parts with multiple and functionally gradient materials, and embed components (e.g., sensors and actuators) during fabrication processes.
- Developing screening methodologies to answer the question of why some materials are processable by AM and some are not.
- Developing tools for AM fabrication of structures and devices atom-by-atom and design for nano-manufacturing.
- Developing and identifying sustainable (green) materials, including recyclable, reusable, and biodegradable materials.
- Developing a shared, standardized third-party data repository that contains AM material standards for data format and analysis and leads to proper choice of AM materials.
- Developing standards and protocols for round-robin production and materials testing.

Materials play a key role in all AM processes. 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 properties.[3,4,20] A significant amount of research remains to be done in developing materials into usable forms for various types of AM machines. The active research topics include, but are not limited to, ensuring that materials demonstrate desired properties in their powdered states and ensuring uniform particle size for powder beds so that melting takes place at uniform rates. While individual AM processes are limited to varying degrees based on these requirements, in broad terms, an impressive variety of materials may be processed by using AM. Figure 6.A.9 shows a hierarchy of homogeneous material systems that have been demonstrated by using AM.[3,4,20] Figure 6.A.10 lists heterogeneous materials.[3,4,20]

Figure 6.A.9 A Hierarchy of Homogeneous Materials Systems for AM[20]

Source: Wohlers Associates

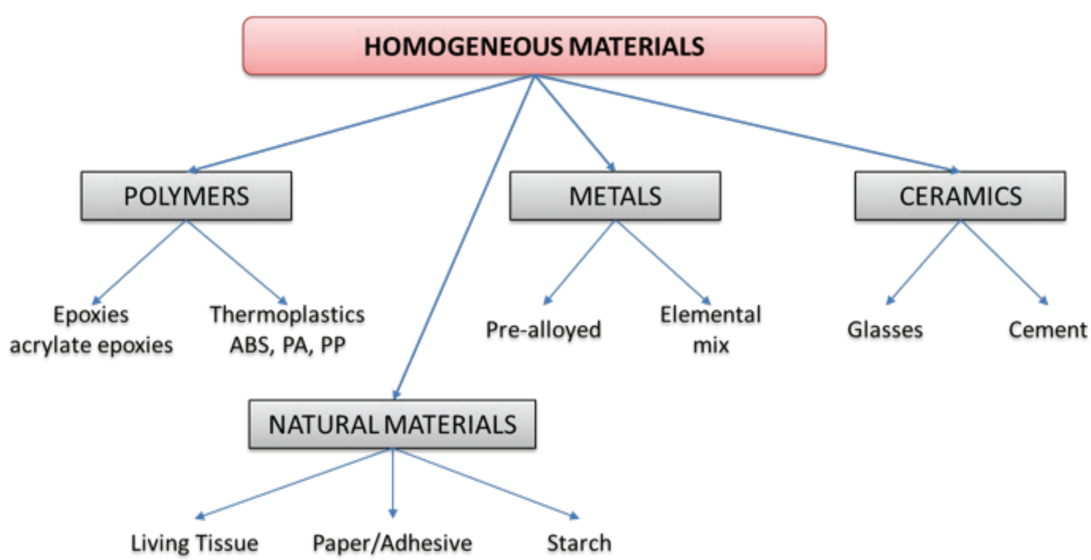
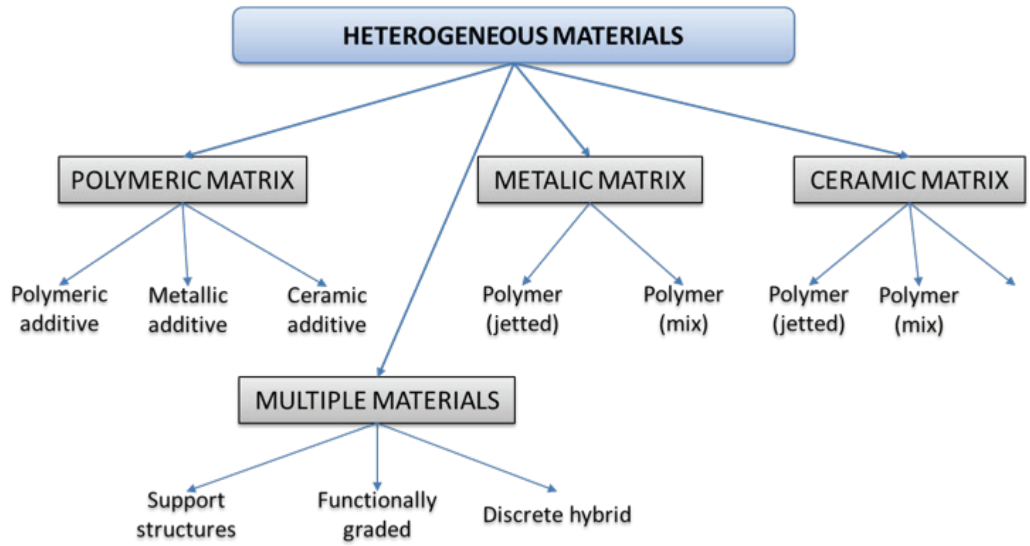


Figure 6.A.10 A Hierarchy of Heterogeneous Materials Systems for AM[20]

Source: Wohlers Associates



Biological composites represent an additional category in the hierarchy of materials. Biological composites often have distinct structures on the nanometer scale that increase desirable properties such as toughness and strength. More R&D is needed to study rapid printing of macroscopic composites.[59]

AM has the potential to improve on CM methods for complex parts made out of metal. AM can reduce waste by repairing worn metal (e.g., titanium) parts and by wasting less metal (e.g., steel) during manufacture of complex parts.[60]

Energy and Sustainability Related Implications

AM technology can reduce material and energy usage and lessen environmental burdens compared with CM processes. Key AM advantages relevant to sustainable manufacturing are less waste because of the nature of the additive process, reduced or in some cases no specialized tooling or fixtures required for AM, ability to build functionally lightweight parts, reduced need for large amounts of raw material within the supply chain, and ability to produce optimized geometries.

For example, the Leading Edge Aviation Propulsion (LEAP) jet engine from GE Aviation and Snecma incorporates fuel nozzles printed with SLS (see Figure 6.A.11).[61] The AM process enabled a simpler design to be adopted for the nozzle, reducing the number of required braze and weld joints from 25 to just five. The resulting nozzle was 25% lighter and five times more durable and contributed to a 15% reduction in fuel burn in comparison with the previous model produced via CM.[62,63.64]

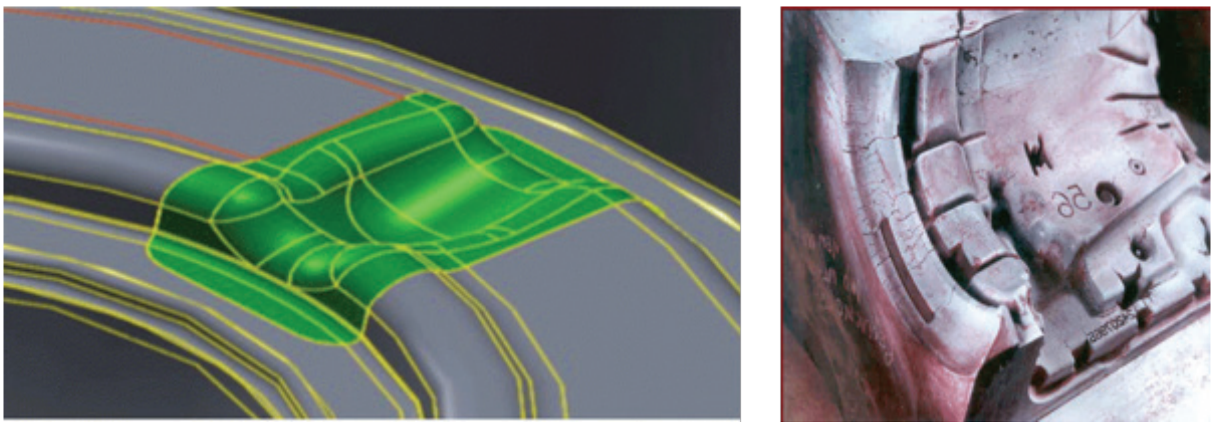
Figure 6.A.11 Jet Engine Nozzle Produced by GE and Snecma for the LEAP Engine by Using Additive Manufacturing[61]

Credit: General Electric Company

Another example is the use of AM for repair and remanufacturing of die-casting dies. Figure 6.A.12 shows a section of a die surface where AM was able to restore finish details in a part damaged by thermal stresses induced during manufacturing. Use of AM for repair and remanufacturing has an ability to reduce the material waste and amount of landfill. It could also reduce energy and matter consumption during manufacture because existing components are used.

Figure 6.A.12 Section of a Die Surface Where Additive Manufacturing Was Used to Restore Finish Details After the Part Was Damaged by Thermal Stresses Induced During Manufacturing[65]

Credit: North American Die Casting Association and Case Western Reserve University



Research opportunities relating to energy and sustainability include the following:[22]

- Designing energy system components to take advantage of AM capabilities
- Pursuing maintenance, repair, and overhaul as a potential AM application
- Developing equitable indicators for measuring sustainability in AM processes and products
- Developing cradle-to-grave LCI of engineering materials for AM processes
- Identifying sustainable engineering materials for AM processes

Education

AM technologies offer significant opportunities that will become increasingly important as further R&D addresses the challenges identified above. Yet many small and medium enterprises may not be able to capture these AM opportunities because they often have limited R&D funds, even though they might be able to benefit the most from AM capabilities. They also face the chicken-and-egg problem that even being able to invest some of their limited resources in AM, they will have difficulty hiring an AM industry workforce, as the training for these skilled jobs is largely unavailable. Approaches such as the following could be considered to support workforce development as demand for these skills develops:

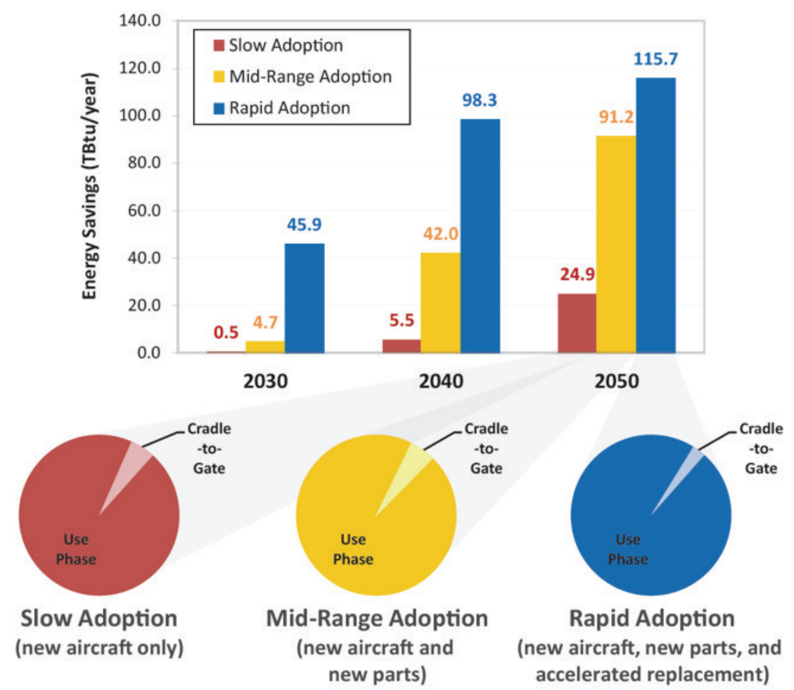
- Developing university courses, education materials, and curricula at both the undergraduate and graduate levels as well as at the technical college and high school levels[22]
- Educating the industry workforce on the free-form design and other important aspects of AM and developing training programs for industry practitioners with certifications given by professional societies or organizations[22]
- Helping industry to adopt AM technologies to reduce life-cycle energy and GHG emissions, lower production cost, and create new products and opportunities for high-paying jobs

Potential for Future Energy Savings and Improved Sustainability from Lightweighting Aircraft

The world's aviation fleet consumed about 10 quads of fuel in 2009 and the fuel use is projected to triple by 2050, growing at a faster rate than any other transportation mode [IEA, "World Energy Outlook", IEA, France 2010]. Aircraft lightweighting is a critical strategy for manufacturers to improve fuel efficiency during operation. Each 100kg reduction in the weight of an aircraft is estimated to save 12–19 billion Btus of fuel over its 30-year lifespan, resulting in annual fleetwide primary energy savings of 25-116 TBtu depending on adoption rate, as shown in Figure 6.A.13.[66] It is about 600–900 times the fuel saving from the same amount of weight reduction in light duty vehicles over the vehicle lifetime. Additionally, reducing weight also saves materials, and the energy related to produce the materials and manufacture them into the final parts.

With the ability to create complex shapes, Additive Manufacturing (AM) enables the design of parts that can be made to the same functional specifications as conventional parts, but with less material. In aircraft, an AM part could achieve more than 40% mass reduction.[67] It is estimated that 4–7% of the aircraft empty mass could be potentially reduced through the adoption of metal AM components in selected systems.[68] This is equivalent to about 1,600–2,800 kg weight reduction for an average size aircraft. If the technology is rapidly adopted in the U.S. fleet, AM enabled lightweighting aircraft could save as much as 115.7 TBtu/year in addition to 4000 ton/year of aluminum alloys, 7600 ton/year of titanium alloys, and 8100 ton/year of nickel alloys in 2050.

Figure 6.A.13 Fleet-wide primary energy use implications of AM Adoption[68]



Noncompetitive collaboration between additive manufacturing companies (machine as well as material manufacturers) and educational entities could play an important role in developing industry standards, educational curricula, and in educating the industry workforce. Government as well as national labs could also play appropriate role and help private sector with the educational and workforce development activities.

Community and Standards

Developing AM communities, technical subcommittees, and internationally recognized standards will play a preeminent role in all aspects of AM technologies. To do this will require activities such as the following:

- Developing and adopting internationally recognized standards (such as those recently initiated by ASTM Committee F42) that are useful to product, process, and material certification[22]
- Ensuring that existing standards organizations have the capabilities necessary to qualify AM manufactured components resident in their organizations

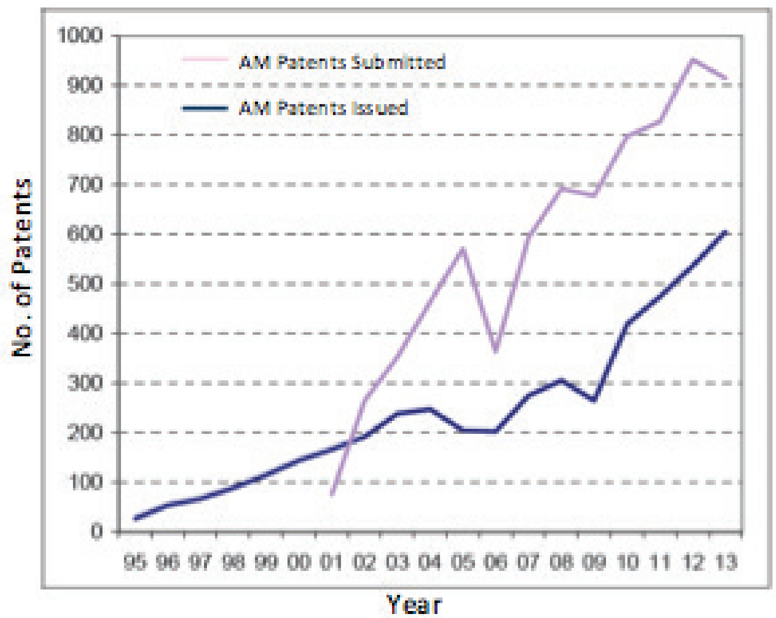
Program Considerations to Support R&D

Public and Private Sector Activities to Date

Figure 6.A.14 shows the growth in issued AM patents since 1995 and the growth in patent applications since 2001. The number of patent applications had been increasing, approximately linearly, since 2009.[3]

Figure 6.A.14 Number of AM Patents Submitted and Issued Between 1995 and 2013[3]

Credit: Wohlers Report 2014



Noncompetitive collaboration has played an important role in the development of the AM industry. Collaborations also occur among educational entities and working groups dedicated to establishing AM industry standards and educational curricula.

The following groups or organizations are playing important roles in R&D of AM processes and technologies. For more details on these groups and organizations, refer to Wohlers' 2014 report.[3]

- **Consortia and collaborations.** The types of noncompetitive collaboration include user groups, online forums, social media, industry roadmaps, industrial consortia, conferences, and other events. AM consortia and collaborative activities include the following:
  - America Makes
  - U.S. Government Interagency AM Working Group
  - Additive Manufacturing Consortium
  - Direct Manufacturing Research Center
  - ASTM International Committee F42
  - Project Technician Education in Additive Manufacturing
- **U.S. Government-sponsored R&D.** Federal agencies in the United States (NSF, Department of Defense, National Institutes of Health, Department of Energy [DOE], etc.) actively support research in AM and its applications. Federal agencies fund universities and private corporations to conduct fundamental as well as application-oriented research in AM.

- **U.S. national laboratories.** DOE national laboratories are active in AM R&D, including particularly the following:
  - Lawrence Livermore National Laboratory
  - Los Alamos National Laboratory
  - Oak Ridge National Laboratory
  - Sandia National Laboratories

For more details on these groups and organizations, refer to Wohlers' 2014 report.[3]

Risk and Uncertainty, and Other Considerations

Risk and Uncertainty Issues

The following risk/uncertainty issues related to AM are identified as well as how these issues impact R&D:

- The AM industry may face intellectual property issues. It is likely that inexpensive access to AM will further strengthen Internet distribution brands and channels at the expense of the originators of novel products.[52] The original data files created for the design of a product are difficult to protect by copyright law, and dealing with misuse of these files could be legally difficult. Also problematic will be the creation of "rival" data files to create objects very similar to the original protected product, where the scope of protection for the same work may vary in different countries.[52]
- The AM industry may need to deal with product liability issues. Collaboration and cooperation will be needed between original manufacturer, third party manufacturer, retailer, and regulator. In a world where AM becomes commonplace, it will be up to the consumers to check that they are buying product design software from a reputable, traceable source. In that way, they will have recourse should a product they produce be defective and/or cause damage or injury.[52] It should be noted that whereas for CM there is a well-established pathway for recourse, for AM there may be additional steps in the process—it is not just whether the software pattern or tooling was correctly designed, or that the resin was the appropriate quality, but also whether the AM process did not suffer a momentary power glitch, etc., all of which greatly increase the difficulty of identifying the source problem and determining recourse.
- The variety of new materials introduced to AM (epoxy resins, elastomers, etc.) needs additional studies to determine the long-term effects on humans and the environment.[10]
- R&D into the solvents to remove AM material is needed; uncertainty exists over the environmental hazards, toxicity, and chemical degradation of current solvents.[10]
- Nondestructive quality and strength testing of AM parts is needed to confirm and verify that the characteristics, specifications and requirements of the product are met successfully via the AM process compared with their counterparts produced through traditional methods.

Intellectual Property and Economic Policy Considerations

The following policy factors may drive AM technology considerations and choices:[69]

- The sale of digital AM intellectual property, such as STL files, may require new tax regulatory policies, and state sales tax policies may need revision.
- AM supply-chain development will necessitate new definitions of taxable events for supplier and buyer.
- Economic unbalances should be investigated owing to a decreased need for labor in manufacturing and a change in global manufacturing.
- Open source AM technology would allow further development and improvement on the technology, but companies often protect intellectual property to recover investments in AM technology.

Case Studies

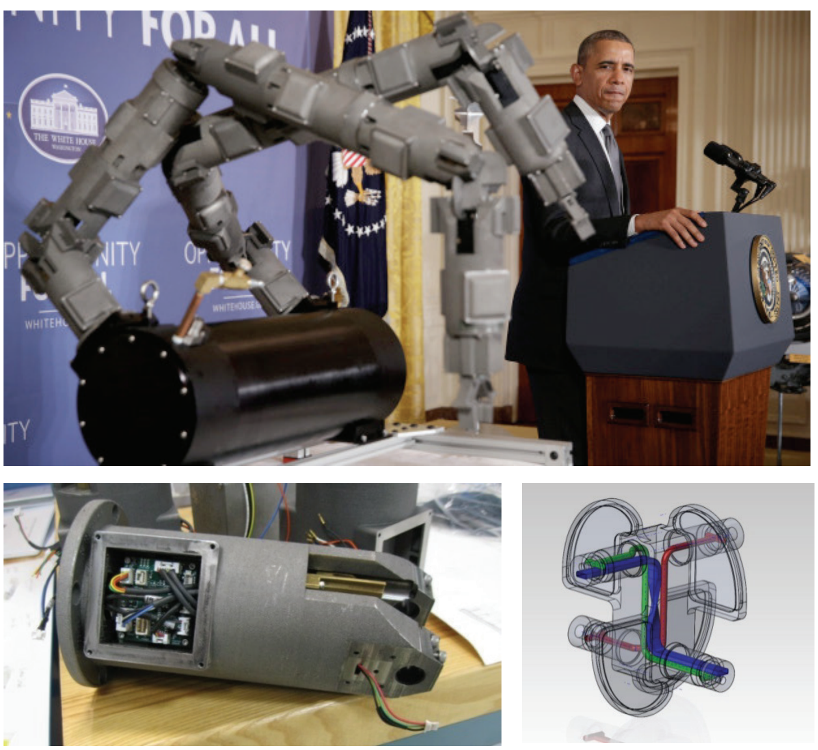
Case Study Application of AM Technologies in Robotic Systems

Army PETMAN is an anthropomorphic robot designed for testing chemical protection clothing. Natural agile movement is essential for PETMAN to simulate how a soldier stresses protective clothing under realistic conditions. Boston Dynamics teamed with ORNL to develop the fully anthropomorphic android for in situ testing of chemical and biological personal protection equipment. The arms of the robot, shown in Figure 6.A.15, were produced by using additive manufacturing (AM) technology.[70,71] The PETMAN system has integrated sensing (chemical), perspiration, thermal management and control (hydraulics), and complex parts that would not be possible with conventional machining.

Highlights of the PETMAN system include the following:

- Robotic arm components produced by AM
- 25 lbs total weight, 60-inch-long arm
- Neutrally buoyant without flotation
- Fluid passages integrated into structure
- Seven degrees of freedom with 180-degree rotation at each joint
- Custom thermal valves for energy efficiency

Figure 6.A.15 President Obama Announces Two New Institutes for Manufacturing Innovation at the White House on February 25, 2015. Shown in the foreground is a robotic arm manufactured via additive manufacturing.[70,71]



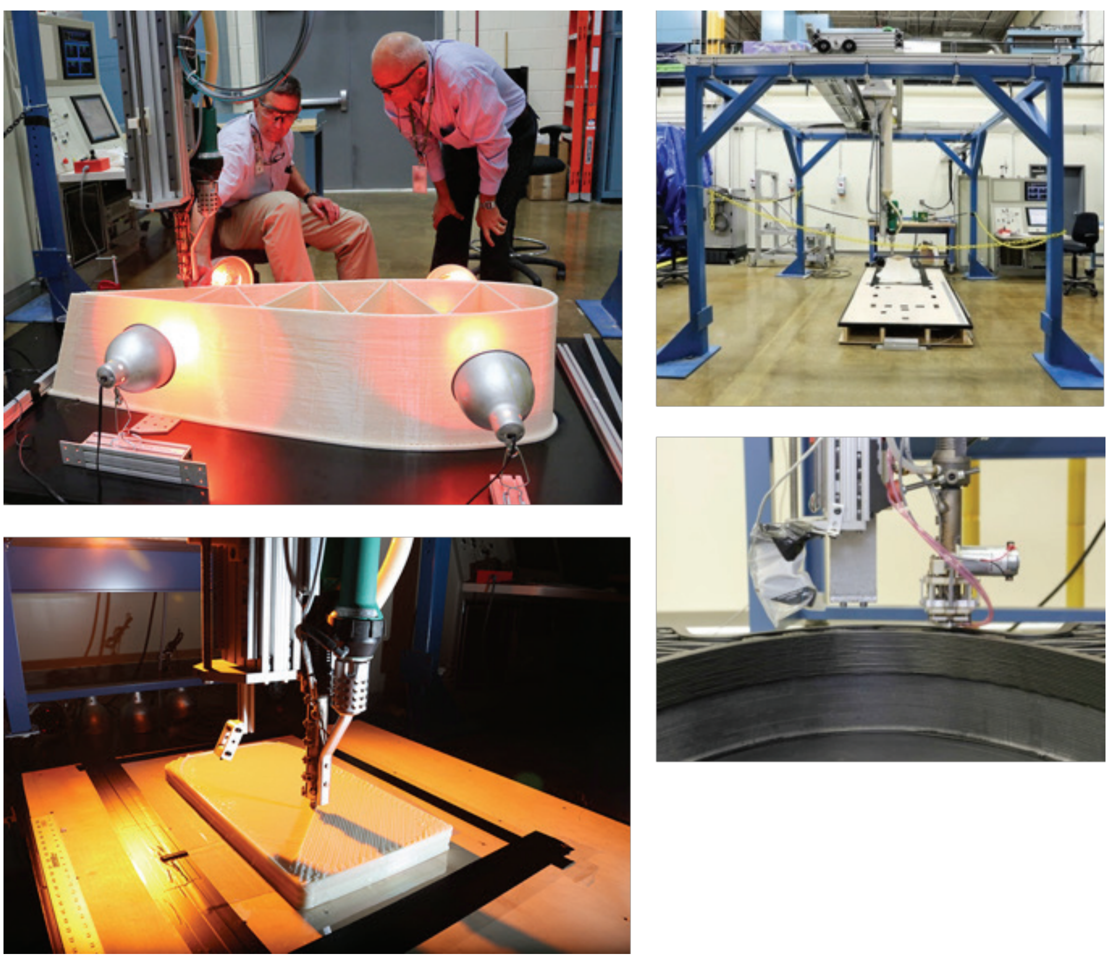
Case Study Big Area Additive Manufacturing (BAAM)

The driving vision for BAAM is a system that is capable of building thermoplastic parts outside of a controlled heat and atmospheric environment. The BAAM system, shown in Figure 6.A.16, combines melting, compounding, and extrusion through a material head attached to a large multi-axis robotic arm or a three-axis gantry. Industry standard materials are used, such as injection-molding pellets, powders, fiber reinforcements, and specialty additives. An important part of the system is the inclusion of computer numeric control (CNC) milling to smooth the low-resolution surfaces.

Highlights of the BAAM system include the following:[71]

- Pellet-to-part pelletized feed replacing filament, enabling a 50x reduction in material cost
- Deposition rate 100x higher than commercially available systems
- Tooling, automotive, aerospace, and robotics applications
- Prototype system 8 feet x 8 feet x 8 feet build envelope.

Figure 6.A.16 BAAM Work at DOE ORNL[71]



Endnotes

[1] Additive manufacturing is a cross-cutting technology with numerous application areas. Additional, indirect connections for additive manufacturing not shown in the diagram include additive manufacturing to reduce use of critical materials (see M. McKittrick, "Additive Manufacturing Meets the Critical Materials Shortage," DOE Office of Energy Efficiency and Renewable Energy (April 9, 2014), available from: http://energy.gov/eere/articles/additive-manufacturing-meets-critical-materials-shortage) and additive manufacturing of components used in harsh service conditions such as high-temperature gas turbines (see "From Powders to Finished Products," Siemens Pictures of the Future (October 1, 2014), available from: http://www.siemens.com/innovation/en/home/pictures-of-the-future/industry-and-automation/additive-manufacturing-from-powders-to-finished-products.html).

[2] "The ASTM International Committee F42 on Additive Manufacturing Technologies." Available at: http://www.astm.org/COMMITTEE/F42.htm.

[3] "Wohlers Report 2014—3D Printing and Additive Manufacturing State of the Industry," Annual Worldwide Progress Report, Wohlers Associates, 2014. http://www.wohlersassociates.com/state-of-the-industry-reports.html

[4] Guo, Nannan; Leu, Ming. "Additive Manufacturing: Technology, Applications and Research Needs." Frontiers of Mechanical Engineering (8:3), September 2013; pp. 215-243.

[5] The Economist, "The Printed World: Three-Dimensional Printing from Digital Designs," 10 February 2011. Available at: www.economist.com/node/18114221.

[6] "The ASTM International Committee F42 on Additive Manufacturing Technologies." Available from: http://www.astm.org/COMMITTEE/F42.htm.

[7] ASTM F2792-12a, Standard Terminology for Additive Manufacturing Technologies,, ASTM International, West Conshohocken, PA, 2012, www.astm.org.

[8] John R. Tumbleston, David Shirvanyants, Rima Janusziewicz, et.al., "Continuous liquid interface production of 3D objects", Science Magazone, Vol 347, Issue 6228, March 23, 2015.

[9] Huang, R.; Riddle, M.; Graziano, D.; Warren, J.; Das, S.; Nimbalkar, S.; Cresko, J.; Masanet, E. "Energy and Emissions Saving Potential for Additive Manufacturing: The Case of Lightweight Aircraft Components." Journal of Cleaner Production, 2015 (in press).

[10] "Additive Manufacturing: Pursuing the Promise—DOE's Advanced Manufacturing Office (AMO)." Available at: https://www1.eere.energy.gov/manufacturing/pdfs/additive_manufacturing.pdf.

[11] Note that recyclability of powders for AM affects materials consumption and is an active research area. See, for example, Wudy, K.; Drummer, D.; Kuhnlein, F.; Drexler, M. "Influence of Degradation Behavior of Polyamide 12 Powders in Laser Sintering Process on Produced Parts." AIP Conference Proceedings, 1593, 2014; p. 691.

[12] Petrovic, V.; Gonzales, J.; Ferrando, O.; Gordillo, J.; Puchades, J.; Grinan, L. "Additive Layered manufacturing: Sectors of Industrial Applications Shown Through Case Studies." International Journal of Production Research (Vol. 49), 2011; pp. 1061-1079.

[13] Nimbalkar, S.; Cox, D.; Visconti, K.; Cresko, J. "Life Cycle Energy Assessment Methodology and Additive Manufacturing Energy Impacts Assessment Tool," Proceedings from the LCA XIV International Conference, October 6-8, 2014, San Francisco, California; pp 130-141.

[14] Computer Science Corporation (CSC), 3D Printing and the Future of Manufacturing, 2012. http://assets1.csc.com/innovation/downloads/LEF_20123DPrinting.pdf

[15] Direct Manufacturing Research Center (DMRC). "Thinking Ahead, the Future of Additive Manufacturing—Analysis of Promising Industries." Gausemeier, I. J., et.al.; Heinz Nixdorf Institute, by order of DMRC, 2011.

[16] Benjamin Grynol, Disruptive Manufacturing – The effects of 3D printing, Deloitte University Press, 2013.

[17] 2014 Global Aerospace and Defense Sector Financial Performance Study. Deloitte University Press, July 2014. Available at: https://www2.deloitte.com/content/dam/Deloitte/global/Documents/Manufacturing/gx-mfg-2014aandd-global-financial-performance-study.pdf.

[18] Bullinger, H. Technology Guide—Principles, Applications, Trends. Springer, Berlin, 2009.

[19] Wohlers Report 2006—Rapid Prototyping and Manufacturing State of the Industry. Wohlers Associates Inc., United Stated of America, 2006.

[20] Bourell, D.; Leu, M.; Rosen, D. "Roadmap for Additive Manufacturing—Identifying the Future of Freeform Processing," 2009.

[21] Hubscher, B. "NASA's Space Launch System Using Futuristic Technology to Build the Next Generation of Rockets." Phys.org (November 7, 2012). Available at: http://phys.org/news/2012-11-nasa-space-futuristic-technology-rockets.html.

[22] Wohlers Report 2003—Rapid Prototyping, Tooling & Manufacturing State of the Industry. Wohlers Associates Inc., United Stated of America, 2003. http://3d-printing-review.com/roadmap-for-additive-manufacturing-identifying-the-future-of-freeform-processing/

[23] Wohlers Report 2010—Additive Manufacturing State of the Industry. Wohlers Associates Inc., United States of America, 2010. http://wohlersassociates.com/state-of-the-industry-reports.html

[24] Wohlers Report 2007—State of the Industry. Wohlers Associates Inc., United Stated of America, 2007. http://wohlersassociates.com/state-of-the-industry-reports.html

[25] "Additive Manufacturing—GE, the World's Largest Manufacturer, Is on the Verge of Using 3-D Printing to Make Jet Parts." April 2013. Available at: http://www.technologyreview.com/featuredstory/513716/additive-manufacturing.

[26] "General Electric's 3D Printing Effort Drives Market." Micro Manufacturing, 2013. Available at: http://www.micromanufacturing.com/content/ge-3-d-printing-effort-drives-market.

[27] World's First Plant to Print Jet Engine Nozzles in Mass Production." July 15, 2014. Available at: http://www.gereports.com/post/91763815095/worlds-first-plant-to-print-jet-engine-nozzles-in.

[28] Langnau, L. "Eye Hospital Takes Flight with Air Duct Made from ULTEM on a 3D Printer." Design World, July 17, 2013. Available at: http://www.designworldonline.com/eye-hospital-takes-flight-with-air-duct-made-from-ultem-on-a-3d-printer/#.

[29] "Additive Value." Phil Reeves, Managing Director of Econolyst, 4th International Additive Manufacturing Conference. September 2009. Centaur Communications, London; pp. 44-45.

[30] "GE Aviation—GE9X engine." Available at: http://www.geaviation.com/newengine.

[31] "Additive Manufacturing—A Game Changer for the Manufacturing Industry?" Roland Burger, Munich, November 2013. Available at: http://www.rolandberger.com/media/pdf/Roland_Berger_Additive_Manufacturing_20131129.pdf.

[32] Helms, Hinrich; Lambrecht, Udo. "The Potential Contribution of Light-weighting to Reduce Transport Energy Consumption," International Journal of LCA, 2006.

[33] Giffi, C.A.; Gangula, B.; Illinda, P. 3D Opportunity for the Automotive Industry." Deloitte University Press, May 2014. Available at: http://dupress.com/articles/additive-manufacturing-3d-opportunity-in-automotive/?id=us:2el:3dc:dup707:awa:dup.

[34] World Rapid Prototyping Equipment Markets. Frost & Sullivan, 2007. http://www.researchandmarkets.com/reports/480632/world_rapid_prototyping_equipment_markets

[35] Cevolini, L.. "Parts That Go on the Final Car." International Conference on Future Industrial Applications of Additive Fabrication, 2006. Euromold 2006, Frankfurt.

[36] Cevolini, L. "Rapid Manufacturing with Carbon Reinforced Plastics: Applications for Motor Sport, Aerospace and Automotive Small Lot Production Parts." White Paper, 2006.

[37] Cevolini, L.; Testoni, G.; Davis, S. "Rapid Manufacturing Application: Motorbike Dash Assembly Made of WINDFORM® XT and SLS Technology." 8th Annual SPE Automotive Composites Conference & Exhibition (ACCE), September 2008, Michigan; pp. 16-18.

[38] "Ducati—Motorcycle Maker Accelerates Engine Design with FDM Prototyping, Stratasys." Available at: http://www.stratasys.com/resources/case-studies/automotive/ducati.

[39] U.S. DOE's Manufacturing Demonstration Facility at Oak Ridge National Laboratory. Available at: http://web.ornl.gov/sci/manufacturing/shelby/.

[40] Benatmane, J. Environmental Report: Delphi Pump Housing. Prepared by Econolyst for the Atkins Project. Available at: http://www.enlighten-toolkit.com/App_Themes/Enlighten/Documents/PumpHousing-processes.pdf.

[41] Data from Statistica, Inc. Accessed from: http://www.statista.com/

[42] "CustomPart.net: Additive Fabrication." USA, 2009. Accessed on January 15, 2015, at: http://www.custompartnet.com/wu/additive-fabrication.

[43] Huang, R.; Riddle, M.; Graziano, D.; Warren, J.; Das, S.; Nimbalkar, S.; Cresko, J.; Masanet, E. "Environmental and Economic Implications of Distributed Additive Manufacturing: the Case of Injection Molding", in preparation, 2015.

[44] "Industrial Tools, Dies, and Molds—Industry Assessment by International Trade Administration." Available at: http://www.trade.gov/static/doc_Assess_ToolsDiesMolds.asp.

[45] Advances in Rapid Prototyping. Frost & Sullivan, 2008.

[46] Wohlers Report 2009—State of the Industry. Wohlers Associates Inc., United Stated of America, 2009. http://wohlersassociates.com/state-of-the-industry-reports.html

[47] Wohlers Report 2000—Rapid Prototyping, Tooling & Manufacturing State of the Industry. Wohlers Associates Inc., United Stated of America, 2000. http://wohlersassociates.com/state-of-the-industry-reports.html

[48] Bourell, D. L.; Leu, M. C.; Chakravarthy, K.; Guo, N.; Alayavalli, K. "Graphite-Based Indirect Laser Sintered Fuel Cell Bipolar Plates Containing Carbon Fiber Additions." CIRP Annals—Manufacturing Technology, 60(1), 2011; pp. 275-278

[49] Guo, N.; Leu, M. C. "Experimental Study of polymer Electrolyte Membrane Fuel Cells using a Graphite Composite Bipolar Plate Fabricated by Selective Laser Sintering." Proceedings of the Solid Freeform Fabrication Symposium. Austin, TX, 2012.

[50] See the Additive Manufacturing Integrated Energy (AMIE) Demonstration project - http://web.ornl.gov/sci/eere/amie/

[51] DUS Architects, Amsterdam. 3D Print Canal House; see: http://dusarchitects.com/projects.php?categorieid=housing

[52] "How to Explore the Potential and Avoid the Risks of Additive Manufacturing." Mayer-Brown, 2013 Report. https://www.mayerbrown.com/files/uploads/Documents/PDFs/2013/June/Three-Dimensional-Thinking-Brochure_Additive-Manufacturing.pdf

[53] "The 3D Printed HOUSE: Technology Is Being Used to Construct an Entire Building—Including the Furniture—in Amsterdam. Available at: http://www.dailymail.co.uk/sciencetech/article-2594234/The-3D-printed-HOUSE-Technology-used-construct-entire-building-including-furniture-Amsterdam.html#ixzz3QnSIr3KI.

[54] Straus, H. "AM Envelope—The Potential of Additive Manufacturing for Façade Construction." Delft University of Technology, 2013. http://books.bk.tudelft.nl/index.php/press/catalog/book/25

55 Scott J Grunewald, ORNL Demos Their New Integrated 3D Printed Home and Vehicle, September 23, 2015. Available at - http://3dprint.com/97217/ornl-demos-amie-project.

56 Snyder, G. H.; Cotteleer, M. J.; Kotek, B. 3D Opportunity in Medical Technology, Deloitte University Press, April 2014. Available at: http://dupress.com/articles/additive-manufacturing-3d-opportunity-in-medtech/?top=4#sup-0.

57 National Institute of Standards and Technology. "Measurement Science Roadmap for Metal-Based Additive Manufacturing," 2013.

58 Hofmann, D.; Kolodziejska, J.; Roberts, S.; Otis, R.; Dillon, R.; Suh, J.; Liu, Z.; Borgonia, J. "Compositionally Graded Metals: A New Frontier of Additive Manufacturing." Journal of Materials Research, (29:17), 2014; pp. 1899-1910.

59 Dimas, L.; Buehler, M. Modeling and Additive Manufacturing of Bio-Inspired Composites with Tunable Fracture Mechanics Properties. Royal Society of Chemistry, 2014. http://pubs.rsc.org/en/Content/ArticleLanding/2014/SM/C3SM52890A#!divAbstract

60 Dey, N.; Liou, F.; Nedic, C. 2012. "Additive Manufacturing Laser Deposition of Ti-6Al-4V for Aerospace Repair Applications." International SFF Symposium, 2012.

61 "World's First Plant to Print Jet Engine Nozzles in Mass Production, July 15, 2014." Available at: http://www.gereports.com/post/91763815095/worlds-first-plant-to-print-jet-engine-nozzles-in.

62 Note that the 15% fuel savings is for the overall technology advances in the LEAP engine, not just the fuel nozzles, which contribute to that number.

63 GE Capital Fall 2013, "Industry Research Monitor: Additive Manufacturing." Available at: http://www.americas.gecapital.com/GECA_Document/Additive_Manufacturing_Fall_2013.pdf.

64 Beyer, C. "Strategic Implications of Current Trends in Additive Manufacturing." American Society of Mechanical Engineers. 2014. available here: http://manufacturingscience.asmedigitalcollection.asme.org/article.aspx?articleid=1909628

65 "Researchers Developing 3D Printing for Die Repair," May 2013. Available at: http://foundrymag.com/materials/researchers-developing-3d-printing-die-repair.

66 Helms, H.; and Lambrecht, U. "The Potential Contribution of Light-Weighting to Reduce Transport Energy Consumption", Int J LCA, 2006.

67 Nimbalkar, S.; Cox, D.; Visconti, K.; Cresko, J. "Life Cycle Energy Assessment Methodology and Additive Manufacturing Energy Impacts Assessment Tool," Proceedings from the LCA XIV International Conference, October 6-8, 2014, San Francisco, California; pp 130-141.

68 Huang et al. "Energy and Emissions Saving Potential of Additive Manufacturing: The Case of Lightweight Aircraft Components", J Cleaner Production, 2015.

69 Cozmei, C.; Caloian, F. "Emerging Markets Queries in Finance and Business: Additive Manufacturing Flickering at the Beginning of Existence." Procedia Economics and Finance, 2012.

70 Dehoff, R. (ORNL). "Additive Manufacturing: Technology and Applications." Natural Gas Infrastructure R&D and Methane Emissions Mitigation Workshop, November 2014. Available at: http://energy.gov/sites/prod/files/2014/11/f19/NG-infrastructure-workshop_ORNL-MDF-presentation.pdf.

71 Blue, C. (ORNL). "Manufacturing Demonstration Facility. Presented in May 2014 in Oak Ridge, Tennessee. More information about activities at the MDF is available here: http://web.ornl.gov/sci/manufacturing/mdf/

Acronyms

ABS	Acrylonitrile Butadiene Styrene
AM	Additive manufacturing
BAAM	Big area additive manufacturing
CAD	Computer-aided design
CAE	Computer-aided engineering
CAM	Computer-aided manufacturing
CM	Conventional manufacturing (generally refers to subtractive techniques in this technology assessment)
DED	Directed energy deposition
DMD	Direct metal deposition
DMLS	Direct metal laser sintering
EBM	Electron beam melting
FDM	Fused deposition modeling
FEF	Freeze-form extrusion fabrication
MJM	Multi-jet modeling
RFP	Rapid freeze prototyping
SLM	Selective laser melting
SLA	Stereolithography
SLS	Selective laser sintering

Glossary

3-D Printing	Synonym for additive manufacturing.
Acrylonitrile Butadiene Styrene (ABS)	A thermoplastic polymer commonly used in industrial 3D printers.
Additive Manufacturing	The process of producing three-dimensional objects directly from computer-aided design (CAD) model data, usually by adding material layer upon layer. Additive manufacturing can be contrasted to conventional subtractive manufacturing methods that involve the removal of material from a starting work piece.
Additive Systems	Machines used for additive manufacturing (also called 3-D printers).
Big Area Additive Manufacturing (BAAM)	A large-scale, gantry-based additive manufacturing machine used to produce large printed objects. The BAAM system is currently under active development by Cincinnati, Inc. and Oak Ridge National Laboratory.

Binder Jetting A process in which a liquid bonding agent is selectively deposited to join powder materials.

Build Envelope The dimensions of a 3-D printer's maximum physical build volume, given by the X, Y and Z axes.

Build Volume The total volume of the build envelope within which a 3-D printer is capable of building a model.

Curing The process of permanently converting to a solid phase a thermosetting polymer, often through the application of heat, electromagnetic energy, or chemical additives.

Directed Energy Deposition (DED) An additive manufacturing process in which focused thermal energy (such as from a laser) is used to fuse materials by melting as they are being deposited.

Electron beam melting (EBM) An additive manufacturing technique that involves the fusion of a metal powder or wire to form an object using an electron beam

Extrusion The process of pushing a fluid build material (e.g. a thermoplastic above the glass transition temperature) through a die or orifice in order to build up a 3-D object as it cools and solidifies.

Freeze-Form Extrusion Fabrication An additive manufacturing process involving the extrusion of aqueous ceramic pastes in a freezing environment, allowing for solidification of each layer during the build process, followed by freeze-drying to remove water content from the finished object.

Filament A wire comprised of build material, generally polymer or metal, used as a feed in many types of 3-D printers.

Fused deposition modeling Terminology trademarked by the Stratasys Company to describe an extrusion-based additive technology, also known generically as fused filament fabrication. The process generally uses a thermoplastic filament that is heated above its glass transition temperature, which is then forced through a nozzle of the additive machine that follows a numerically controlled path to create a 3-D build volume.

Material jetting An additive manufacturing technique that creates objects in a method analagous to a two-dimensional ink jet printer. Material is deposited through a nozzle, or "jetted" onto the build surface or platform, where it solidifies; and the model is built layer by layer. In multi-jet modeling (MJM), a printhead consists of hundreds of jets arranged in an array.

Photopolymer A liquid thermosetting resin that hardens permanently when exposed to light. The thermosetting reaction generally requires photoinitiators that are responsive at specific frequencies of light.

Rapid prototyping A group of techniques used to quickly fabricate a scale model of a physical part using three-dimensional computer aided design (CAD) data.

Selective Laser Melting (SLM) An additive manufacturing technique in which focused energy from a laser beam is used to melt and fuse metal powders together to form objects. Selective laser melting is distinct from the related technique selective laser sintering (SLS) because in SLM the powder is fully melted, whereas in SLS the powder is compacted (sintered) through heat and pressure.

Sheet lamination	A method of building parts by trimming sheets of material and binding them together in layers.
Stereolithography (SLA)	An additive manufacturing process in which laser light is used to “draw” a computer-programmed design onto a photopolymer resin vat, solidifying the resin. The process is repeated layer by layer to produce a 3-D object.
Subtractive Manufacturing	Manufacturing processes based on controlled material removal through cutting or drilling (as opposed to additive manufacturing, where layers of material are added successively to form an object.)
Thermoplastic	A class of polymers that exhibit the reversible phenomena of softening when heated and solidifying when cooled.
Thermoset	A class of polymers formed from a (liquid/viscous/soft solid) resin that is cured to initiate polymer cross-linking, permanently hardening the material into a solid phase.
Tool, tooling	Mold, die, fixtures, or other device used in manufacturing processes.