FASTLANE & University of Dayton

Technology Roadmap of Additive Manufacturing in Ohio

Exploring Opportunities to Cultivate Ohio’s Additive Manufacturing Sector

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Introduction

FASTLANE, the West Central Ohio MEP Center, is proud to present this Additive Manufacturing (AM) Roadmap to the Ohio Manufacturing Institute. Its purpose is to support the State of Ohio’s initiatives to optimize the State’s growth strategy in support of its budding additive manufacturing sector. The Roadmap is based on the work of the Ohio Manufacturing Institute (OMI), which has guided and sponsored the project. The report’s researchers and writers include elements of FASTLANE, and the University of Dayton Research Institute with support from prominent members of Ohio’s additive manufacturing private sector.

Purpose:
The objective and desired outcome of this study is twofold.

1) To better prepare policymakers to cultivate Ohio’s growing AM Market,
2) To provide a comprehensive AM Market Study that can act as a guide for companies that are either already in, or could exploit the AM marketplace to help Ohio manufacturers gain an economic advantage over outside competitors.

This report achieves these objectives and desired outcomes by:

1. Analyzing additive manufacturing market conditions,
2. Developing a methodical and living research methodology that can be easily reused in future studies,
3. Identifying gaps and growth opportunities within the AM Market,
4. Recommending optimized actions that the State of Ohio can undertake to grow its competitive advantage in the AM marketplace.

Scope:
This report incorporates analysis from most aspects of the additive manufacturing marketplace. Major themes include:

1. Current and future AM technologies
2. Identification of gaps and barriers to Ohio’s exploitation of AM
3. Current and future use of AM by individual market sectors in Ohio
4. Trends in AM production and supporting services
5. Recommendations in support of Ohio overcoming challenges in AM

This report is specifically tailored towards accelerating Ohio’s competitive advantage in the United States’ AM marketplace between 2014 and 2024.

One of the most difficult challenges the authors of this report have faced is the multi-disciplinary nature of AM. Our analysis suggests that AM, in the future, could replace virtually every traditional manufacturing process such as molding, machining, joining, casting, etc. This makes it extremely difficult, if not impractical, to approach AM as a standard manufacturing process.
Additionally, while we have interfaced with Ohio AM manufacturers, the over-reliance on an AM survey is problematic when compared to roadmaps focusing on more traditional manufacturing processes: there are very few “true” AM manufacturers. That is, the vast majority of AM manufacturing is used to augment processes used by manufacturers that would traditionally be categorized as a company specializing in another process. For example, a manufacturer that specializes in traditional molding might have a small AM capability either for experimentation or for very specific parts.

Compounding the problems of approaching AM as a typical manufacturing method is the small market size and its relatively recent adoption for broader manufacturing use. Despite an annualized 25-30% growth rate, the entire worldwide AM market is less than $3.5B in 2014; this amount is miniscule in comparison to the broader manufacturing market. Additionally, in spite of having its origins in the 1980s, the private sector only began to embrace AM on a larger scale in the 1990s; broader runs began in the latter part of the first decade of the 2000s.

As such, this report focuses on barriers and bottlenecks in the adoption of AM, current and future uses within manufacturing industries (e.g. aerospace, automotive, medical, etc.), and recommendations to support Ohio’s AM industries.
Executive Summary

Additive Manufacturing (AM) is an umbrella term for the use of any production technology that utilizes a computer controlled material layering system to produce three dimensional components.

Widespread adoption of AM across all sectors and processes within Ohio’s manufacturing sector requires overcoming many challenges over the next decade. Rather than addressing these challenges in terms of specific technical issues, this report focuses on broader trends, themes, and concepts within the AM sector to better inform policymakers on how they can help to foster Ohio’s budding AM industry. In support of this effort, the authors of this roadmap have organized the primary barriers to AM into the following categories:

_Gaps and Barriers_

1. **Cost:** Machines, Materials
2. **Material Types:** Metals, Multi-material Components, Availability (Proprietary and Patents), Organic Fibers, Malleable Products, Thermal Resistant
3. **Production Speed:** Pre-processing, Printing, Post-processing
4. **Education:** Universities, Trade Schools, Certifications, Workshops
5. **Standardization:** Processes, Quality Control, Industry Standards, Regulations, Software Integration

This Roadmap defines six manufacturing sectors in which Ohio’s AM will see particularly strong growth over the next decade. While all the categories apply to each sector in one degree or another, particularly factors such as cost, most sectors are particularly sensitive to specific barriers.

_Additive Manufacturing Market Sectors_

i. **Automotive:** Cost, Material Types, Production Speed
ii. **Medical:** Material Types, Standardization
iii. **Consumer Products:** Cost, Production Speed
iv. **Aerospace and Defense:** Material Types, Standardization
v. **AM Machines:** Cost, Production Speed, Education
vi. **AM Materials:** Cost, Material Types, Education

This report uses a methodology that is both quantitative and qualitative that utilizes market, patent, and journal article data to provide a market potential analysis by industry of the growing AM market. The output of this methodology is a set of three values (called Opportunity Values or OVs) representing short term, long term, and total AM market potential in Ohio over the next decade for the most promising industries. The higher the OV for an industry, the higher the rate of return will be on investment for Ohio policies that support said industry.
### Categories

<table>
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<th>Short Term O.V. (0-5 Years)</th>
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<td>Printers &amp; Materials</td>
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According to the opportunity values:

- **Medical products**
  - *Highest* opportunity values over the next decade
  - *Lowest* opportunity value growth rate (15%) between short and long term values – this suggest the consumer products industry will have the least potential post 2025.

- **Consumer Products**
  - *Lowest* significant potential over the next decade
  - *Highest* opportunity value growth rate (25%) between short and long term values – this suggest the consumer products industry will surpass all other categories after 2025.

### Action Plan

For the purpose of approach/policy, we suggest Ohio policymakers prioritize initiatives relating to the five Gaps and Barriers. Additionally, two overarching themes policymakers may consider to expand AM in Ohio is to support actions, policies, and initiatives designed to 1) Integrate AM technology into existing core products of Ohio manufacturers 2) Improving printing processes to make current AM cheaper, faster and more efficient.
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Methodology

This market study has been particularly challenging due to its focus on an emerging manufacturing technology with an additional specialization of analyzing how Ohio can leverage and optimize its current manufacturing sectors to meet these future market conditions. The combination of the uncertain nature of a market in its infancy with the need of a very specific objective severely limits the amount of data available to achieve the objective of a market study.

Market studies focusing on other manufacturing sectors with similar purposes tend to almost exclusively rely on either market polling or the examination of secondary sources and/or historical trends. However, these methods have severe shortcomings for the production of this market study on AM. Market polling requires a sufficiently large number of businesses specializing in the industry to add substantial value. The problem is, AM is just beginning to evolve from simply augmenting other manufacturing processes into being a core business for manufacturers.

For example, AM has long been popular for use in rapid prototyping. However, after finishing a prototype, a manufacturer would use traditional production processes to build components sold to consumers. As such, most companies that utilize AM in Ohio cannot reliably be classified as additive manufacturers, but only as AM users. Utilizing secondary sources and historical trending have a similar issue – there simply isn’t much information on the AM marketplace. This led us to experiment with other possible methodology that can be utilized specifically for analyses to overcome these constraints studying the AM market.

We developed an original methodology that combines qualitative and quantitative approaches. Additionally, it has been specifically tailored to function as a living document. That is, additional information can be added to this methodology over the next decade, preventing a simple “snapshot” of the industry and adding value well into the future.

Another strength of the methodology of this report is the ability to analyze AM technologies and sectors against each other in an easily digestible manner that otherwise would be difficult to compare. The end result was a hybrid methodology specifically designed to incorporate many elements of different projection techniques providing policymakers and manufacturers with the most accurate roadmap on AM.

Perhaps the most ambitious concept this roadmap employs is going beyond merely predicting what future AM technologies will be critical in that it provides a timeframe in which individual markets will mature over the next ten years.

The Qualitative

Apart from consulting with subject matter experts in AM, the authors of this report have studied and collected over 60 pieces of relevant literature from a variety of media including magazines, newspapers, books, frameworks, government documents, think tanks and scientific publications.
Much of this qualitative research has been critical for identifying what technologies within each identified important sector is of particular importance.

**The Quantitative**

While our qualitative research identifies innovative technologies and sectors, it does not do as good of a job predicting which AM sectors will be of particular importance.

As such, the report’s authors conducted data mining for each manufacturing sector. Data was compiled on the current and future locations of AM, as well as which sectors provide Ohio with the most opportunities. We compared the number of journal publications, the number of patents, and changes in market sizes for AM sectors between 2003 and 2013. We utilized both absolute and year-over-year growth as part of the final model.

For absolute and growth values for journal articles and patents, we averaged the results from searching specific key terms within the Google Scholar and Google Patent databases. This was done at both the national and state level.

The equation was completed twice for both the United States and Ohio to provide a method to compare Ohio with competing states. Due to the length and complexity, the full equation can be found in the appendix section of this report. It is important to note that since AM is still in its infancy, collecting the required data was extremely difficult, sometimes with sample sizes smaller than optimal.

The markets for AM systems and AM materials are particularly difficult analyze as a category of industry – it is an enabler for the use of AM in other industries. Another issue in calculating the OV for AM systems and AM materials is a very limited amount of information on not only the Ohio market for these industries, but the U.S. AM market as a whole. There is however, estimates for the percent AM systems and AM materials are of the total AM market at an average of 13% and 18% respectively. Since both are an enabler of the other four major industries, OV for AM systems and AM materials were calculated by multiplying their respective percent of the market by the sum of the other OV.

**Manufacturing Categories and Sectors**

In support of the Roadmap’s effort to recognize bottlenecks that hinder the growth of Ohio’s AM market, the authors have organized barriers into the following categories:

1. Cost
2. Material Types
3. Production Speed
4. Education
5. Standardization

Additionally, the primary market opportunities by industry over the next decade include:

1) Automotive
2) Medical
3) Consumer Products
4) Aerospace and Defense
5) AM Systems
6) AM Materials

This market study uses both these categories and market sectors throughout this report.
Introduction to Additive Manufacturing

Many traditional manufacturing methods (particularly machining) input raw material and take away, or subtract material to produce a finish product. The manufacturing of the fins of the engine turbine below is an example of subtractive manufacturing. Each metal fin starts as part of a metal sheet/block and excess material is cut until only the required final product is left.

Additive Manufacturing is a process in which material is added; typically utilizing a computer controlled layering process, to make a three-dimensional object. Using the engine turbine example, the whole component (including fins) above was printed via AM. Utilizing a metal powder, this AM process has virtually no waste and allows the printing components with properties that are not possible and/or cost effective if utilizing traditional printing.

The printer head will move and extrude material as directed by computer software

Some higher-end printers have multiple heads/extruders working at once. While two heads are the most common for these printers, there are a few entering the market with four
3D printers widely vary in size from personal home-use printers (typically able to produce objects with build volumes less than 10” x 10” x 10”) to large industrial-scale printers (with the build volume capability of a few cubic feet). Despite differences in sizes, the fundamental component of printing layers of material to complete a finish project does not change.

A Stratasys Objet1000 3D printer designed for industrial use and can print objects up to 39.0” x 31.4” x 19.6”

A recent Makerbot 3D printer designed for home use capable of printing small ABS plastic components up to 11.2” x 6.0” x 6.1”

There are many benefits for Ohio manufacturers to utilize AM including:

1. Customization of components
2. Enhanced performance of products
3. Light weight parts
4. Lower energy intensity
5. Less waste
6. Reduced time to market
7. Rapid innovation
8. Agility and flexibility (such as printing spare parts on-site and on demand)

Despite the AM market growing at an annualized rate of ~30% the past five years, the market is still very small – roughly $3.5B. As such, when defined as a distinct manufacturing process, AM has a tiny footprint when compared to more traditional techniques. However, AM’s versatility and its potential for augmenting or completely replacing most traditional manufacturing methods has the potential to be as disruptive as the introduction of the assembly line at the turn of the 20th century.
Additive Manufacturing Technologies
As previously stated, all major 3D printing technologies function in fundamentally the same way – they layer material to produce a 3D object. However, there are a number of different technologies and techniques used for layering material. The use of each of these is associated with advantages and disadvantages typically related to application, cost, speed, process, and product. Perhaps the seven most common are:

1. Vat Photopolymerization

Vat photopolymerization technology, also known as stereolithography, uses a vat of liquid photopolymer resin, from which the model is built layer by layer. The shape stand is dropped from the top of the resin vat downwards by the layer’s thickness. An ultraviolet (UV) light is used to cure or solidify the resin where needed; the platform then continues moving downwards, and additional layers are built on top of the previous layers. At the end, the vat is drained of resin and the object is detached.

- **Materials**: Plastics and polymers
- **Advantages**: High level of accuracy, and good finish, relatively quick process, typically large build areas
- **Disadvantages**: Relatively expensive, extensively post processing, limited materials, frequently required support

2. Material Jetting

Binder jetting, originally invented by MIT, uses powdered materials in a powder bed. The materials are selectively joined together by a liquid bonding agent through inkjet print head nozzles. Binder jetting is similar to material jetting; however, the difference resides in the fact that the jetting material is not the build material. In this process, the print head selectively deposits the binder adhesive on the top of the powdered material, which is spread over the build platform by the use of a roller. Another layer of powder is then spread on the previous layer and the process is repeated until the object is completed.

- **Materials**: Polymers, waxes, and plastics
- **Advantages**: High level of accuracy, good finish, relatively quick process, typically large build areas, colors
- **Disadvantages**: Relatively expensive, lengthily post processing time and removal resin, limited material, often requires support structures and post curing for parts to be strong enough for structural use

3. Binder Jetting
Binder Jetting uses powder materials in a powder bed are selectively joined together by a liquid bonding agent through inkjet print head nozzles. Binder Jetting is similar to material jetting but the difference resides in the fact that the jetting material is not the build material. The binder is usually a liquid and the build material is in powder form. The print head selectively deposits the binder adhesive on the top of powder material spread over the build platform using a roller. Another layer of powder will spread on the previous layer and the binder material will be selectively joining the materials.

- **Materials:** Metal, polymers and ceramics
- **Advantages:** The two material methods allows for a large number of different binder-powder combinations allowing for the printing of products with an usually wide range of mechanical properties, colors
- **Disadvantages:** Not always suitable for structured parts due to the use of binder material, significant time with post processing

4. **Material Extrusion**

In material extrusion, the build material is first drawn through a nozzle, where it is melted. It is then selectively deposited layer by layer, where the material is cooled until the object is formed. The most common material extrusion process is Fuse Deposition Modeling (FDM), a process developed by Stratasys. It is widely used for domestic and hobby 3D printings.

- **Materials:** Polymers (ABS, nylon, Polycarbonate, Thermoplastics)
- **Advantages:** Widespread and inexpensive process; ABS plastic, which has good structural properties and is easily accessible, can be used
- **Disadvantages:** Nozzle radius limits and reduces the final quality; accuracy and speed are low when comparing to other processes, accuracy of the final model is limited to material nozzle thickness. Constant pressure of material is required in order to increase quality finish

5. **Powder Bed Fusion**

Powder Bed Fusion (PBF) utilizes a laser or electron beam to melt and fuse material powder together. In this process, a thick layer of material (0.1mm) is spread over the build platform; the laser or electron beam then fuses the first-layer cross section of the model. The layer of material is then spread again using a roller. The process is repeated until the desired object is obtained. Any loose and infused powder is removed during post processing.

The technology uses different processes, such as direct metal laser sintering (DMLS), electron beam melting (EBM), selective heat sintering (SHS), selective laser melting (SLM), and selective sintering (SLS).
• **Materials**: Any powder-based materials, commonly metals and polymers

• **Advantages**: Relatively expensive as compared to other AM processes, suitable for visual models and prototypes, ability to integrate technology into small scale, office sized machine, powder acts as an integrated support structure, large range of material options – particularly metals

• **Disadvantages**: Slow speed, lack of structural properties, size limitations, high power usage; finish is dependent on powder grain size

6. **Sheet Lamination**

Sheet lamination technology uses processes such as ultrasonic additive manufacturing (UAM) and laminated manufacturing (LOM). UAM uses sheets or ribbons of metal (aluminum, copper, stainless, steel, and titanium) in ultrasonic welding. The LOM process is a layer-upon-layer approach using paper as printing material and adhesive instead of welding.

• **Materials**: Metals (aluminum, copper, steel, titanium, etc.)

• **Advantages**: Relatively fast, low cost, ease of material handling, cutting can be very fast, relatively little energy uses

• **Disadvantages**: Finish can vary depending on paper or plastic material, post processing is often required, limited material use, and fusion processes require further advance research

7. **Direct Energy Deposition**

A direct energy deposition (DED) machine consists of a nozzle mounted on a multi-axis 4” x 5” arm, which deposits material onto a specified surface; the material is then solidified. It is mostly used in repairing and maintaining structural parts. Material is either provided in wired or powdered form. Laser beams, electron beams, or plasma arcs melt the material upon deposition. Further material is then added and the process is repeated till the desired shape is obtained.

The DED is also called laser-engineered net shaping, directed light fabrication, direct metal deposition, 3D laser cladding.

• **Materials**: Cobalt, chrome, titanium

• **Advantages**: Ability to control the grain structure to a high degree, which lends the process to repair, functional parts, high accuracy.

• **Disadvantages**: Require post processing, limited material use, fusion process require more research to further advance the process into a more mainstream positioning.

Additional technologies being heavily utilized by Ohio:
While not considered a separate entity from the seven above, two AM technologies of particular interest to Ohio:

- **Big Area Additive Manufacturing - BAAM**
  - Technology being developed at Oak Ridge National Laboratory and commercialized by Cincinnati, Incorporated in Harrison, Ohio
  - Primary use is in the production of large tools for aerospace composites (currently up to 10 feet by 10 feet by 10 feet.)
  - Technology used to 3D print an automobile (called Strati) in 2 days
  - Prints at 500 to 1,000 times the speed of other polymer 3D printers
  - Uses plastic pellets directly (versus filaments)
  - Prints “out of the oven”

- **Arburg Freeformer 3D Printer**
  - Technology developed by Arburg, a German injection molding company
  - Primary use is in prototyping and mold production
    - Uses plastic pellets
Reducing Barriers to Growth

In support of the Roadmap’s effort to recognize bottlenecks that hinder the growth of Ohio’s AM market, the authors have organized barrier reduction strategies into the following categories:

1. **Cost**: Machines, Materials
2. **Material Types**: Metals, Multi-material Components, Availability (Proprietary and Patents), Organic Fibers, Malleable Products, Thermal Resistant
3. **Production Speed**: Pre-processing, Printing, Post-processing
4. **Education**: Universities, Trade Schools, Certifications, Workshops
5. **Standardization**: Processes, Quality Control, Industry Standards, Regulations

**Cost**

Supporting policies that focus on decreasing the cost of existing AM is perhaps the single greatest initiative that Ohio could undertake to secure its future as a leader in AM; cost reduction may take the form of decreasing the cost of the machines themselves, the materials used in production, or software.

*Machines*

Compared to traditional manufacturing methods, AM is new and untested; it is considered something of a niche manufacturing sector. To date, the lack of widespread adoption of AM as a primary production method naturally raises prices due to economies of scale, low product demand elasticity, and limited competition. However, as the technology matures and competition increases, the average cost of AM machines will fall in price to maintain competitive advantage.

*Materials*

A significant cost associated with additive manufacturing that is often overlooked is the price of the material used in the production of components. Like the price of machines, as the technology matures and competition increases, the price of material will decrease. However, it is important to note that some AM product producers are following similar business models to traditional printing methods – sell the printers at a discount and make the profits on selling the raw production materials. Overall however, the costs of materials designed for AM use are almost always (sometimes significantly so) more expensive than similar materials used in traditional manufacturing.

*Patent Protection*

The AM industry is young, and the exclusiveness of critical patents has dramatically increased the price and availability of AM technology. However, many of these early patents are starting to expire, and the introduction of additional competition and generic products is dramatically decreasing the cost of such AM technology. Along with AM machines and processing, patents on raw materials also hinder more widespread adoption.
Material Types

In the short term, policies that support the expansion of metals and metal alloys in AM would almost certainly improve Ohio’s competitive advantage in the wider manufacturing sector. In the long term, supporting research initiatives aimed at developing AM technologies capable of efficiently printing composites and products will be critical for continued growth of AM adoption.

Polymers

Since the inception of AM, the primary raw materials for its use has been polymers, due to favorable material properties (low melting point, easier to mold, holds form well, etc.). Over the years, new polymers have been used with a variety of different performance characteristics such as increasing strength, durability, and ease of use. As the polymer market in AM has matured, polymer AM research has focused on plastics with certain material properties for specific applications.

Of particular interest to Ohio, the University of Dayton Research Institute, Stratasys, RP+M, PolyOne, and aerospace OEMs have formed a primer research and development team designing new polymer systems for the next generation of AM printers.

Metals

The use of metals (the second-most mature field of materials) has exploded over the past few years. Since 2010, there have been significant advances in printing metal, particularly in steel, chromium, and titanium. Within the next few years, AM experts expect to print a much wider array of metals and alloys; the widespread use of exotic metals may take until the 2020s primarily due to low demand.

A major bottleneck is the diversity of metals available for printing, partly due to the difficulty of turning metals into powders. Like in traditional manufacturing, utilizing AM for different metals and alloys requires different techniques and printer qualities. Research for overcoming this barrier is generally incremental in nature, and does not necessarily require additional disruptive technology.

While not often thought of as a typical manufacturing sector, AM is seeing increased use in jewelry and similar aesthetic applications; further, the printing of gold and other precious metals has the potential to transform the industry.

Compared to traditional manufacturing, the untested nature of utilizing AM-produced metal products is a major bottleneck. In particular, many questions exist regarding the properties of printed products when compared with those of traditionally manufactured products. For example, structural integrity is an issue with hard metals, as they have a tendency to crack. This
uncertainty has caused hesitation among many manufacturers with regards to integrating AM technology into their products.

**Medical and Bio-Printing**

While there has been significant progress in the use of AM for medical implants and devices (see Error! Reference source not found. section below), printing organic fibers has received significant interest from researchers within the medical community; everything from skin to organs can be printed. While there has been some success within a laboratory environment, there are significant hurdles to the widespread adoption of AM in a medical setting; these range from cell and material selection to assembly. As such, the marketplace will not see the widespread printing of organic fibers for medical applications until at least the 2020s.

**Non-Rigid Products**

One key shortcoming in AM is the difficulty in printing malleable plastics and metals. The issue is primarily due to the fundamental nature of layering material: the precise fusion of layers is easier to accomplish when a rigid form is used. While commercially-available rubber-like plastics exist, such materials are still relatively new to the market, and often require significant trial and error, additional supports to maintain shape while printing, and the flexible extrusion heads of the printer are often not as precise as printing rigid material. Effective methods to overcome the hurdles of printing non-rigid products will require a significant long-term research and breakthroughs in AM technology.

**Multi-Material Components**

Printing products that use a multitude of different materials is perhaps the “holy grail” of material-focused AM technology. Printing a mixture of different plastics, metals and composites, and other materials in one product presents a number of challenges including differentiation of required heat, extrusion techniques, feeding systems, and other components that have to be specifically tuned for specific materials. While there are printers that can print multiple polymers, more research is required for polymer/metal or metal/metal printing. Fusing many dissimilar materials is notoriously difficult, even in traditional manufacturing, and can require steps that cannot currently be integrated into existing printer technologies.

**Production Speed**

While most of the interest in AM is centered on the actual printing of products, there are actually multiple stages of production that are often underappreciated by new AM manufacturers when determining speed of production. For the purpose of this study, AM has been split into three primary stages:

1. **Pre-processing** refers to everything from designing a product to calibrating/setting up machines for the print
2. **Printing** refers to the physical printing of the product
3. **Post-processing** refers to the cleaning and finishing of products for distribution
Slow printing speed, and perhaps to a lesser extent, pre/post-processing of components, are the biggest speed-related bottlenecks in AM. However, overall, the decreased amount of pre/post-processing required for AM is one of its biggest strengths over traditional manufacturing methods. As such, there will almost certainly be a concerted push towards faster printing speed over the next decade.

**Pre-processing**

The vastly decreased time that is required for pre-processing in AM, as compared to traditional manufacturing techniques, is one of its major strengths for use in rapid prototyping. The major components of pre-processing are the designing of the product, machine setup, and calibration.

A major bottleneck in pre-processing is the need to convert commodity raw material forms (such as pellets) to specialized precursors (like filaments). In addition to simplifying production, it also removes the middle man from the supply chain. Other bottlenecks for pre-processing is a shortfall in education regarding the design and use of 3D printers, and software development and integration - both which are discussed below.

**Printing**

After decreasing cost, slow printing time is perhaps the biggest bottleneck towards the replacement of traditional manufacturing methods with AM technology. This is particularly important in industries requiring mass production on a very large scale – such as automobiles.

In the near term, research has focused on utilizing multiple print heads which increases speed proportionately. However, this type of printing is more expensive and is more complex than traditional manufacturing methods; thus, it is inherently less reliable than those methods. Long-term research will most likely require a significant breakthrough in technology such as decreasing the required movement of printer heads and/or advances in curing different 3D printing materials for faster layering.

**Post-processing**

The effort required in the post-processing of products is often underestimated preproduction. While a printer may be able to print a component, often times said component will need substantial finishing such as removing support material, polishing, painting, and additional surface finishing. This is particularly true for metal components. AM technologies that can minimize post-processing will be vitally important both in terms of decreasing cost and increasing speed.

**Education**

Another bottleneck for AM is the education of designers, engineers, machinists, and other manufacturing personnel of the required skills for the efficient use of AM machines. Many manufacturers have purchased printers over the past few years with only a conceptual understanding of the value of such machines; however, finding and maintaining skilled personnel
on the use of such machines can be more difficult. While AM education is increasing, there are significant initiatives that can be immediately undertaken in Ohio that will position it for the explosive growth that is expected in the use of AM.

The promotion of the study of AM in major and minor engineering degree programs at major universities, particularly in industrial, mechanical, and material science, will help educate engineers. Additionally, programs that provide technical training in the following areas are particularly important:

i. Computer aided design
ii. Machine making, operation, and management
iii. Analysis of finished products
iv. Supply chain and project management

The use of trade schools, AM certification, and adult education are also valuable for hiring specialized AM employees. While there have been such initiatives at local community colleges, such programs are in their infancy; coursework for market needs is still in development.

AM is still relatively unknown to much of the population; this makes recruiting and the maintenance of such programs a challenge. In addition to teaching machine use, upkeep, etc., classes focusing on CAD programs can provide AM manufacturers with valuable technicians.

**Standardization**

The final inhibitors of growth in AM that will be discussed are industry standards and regulation. The theme of the infancy of AM is particularly noticeable in this category, due to its rapid evolution and comparatively small market size.

**Processes**

Within the past decade, industry trade groups have been formed that have been leading much of the push for industry standards in AM processing; notably, the “F42” committee on AM from ASTM has been developing standards since 2009. Historically, manufacturing industry trade groups have been relatively successful in developing their own standardization processes with government participation; sometimes, this intervention is primarily focused on safety issues.

**Quality Control and Regulations**

Quality and regulations typically go hand-in-hand. This is due to the need for products to both meet the parameters that are advertised to customers and safety considerations for products, such as the failure of a critical component due to poor quality.

Quality control may be a particular problem in the AM industry, due to the growing affordability of AM machines and the increasing versatility and acceptance of products that are printed. Regulations should cover the process that is utilized, the material that is used, and the design of the product.
Perhaps often overlooked is the importance of regulating the types of products that may be printed. An example regards the manufacture of weapons and other restricted products; instructions for the printing of firearms have been released on the internet.

**Software**

Software suite improvements user interfaces, consistency, and capabilities will organically evolve around new AM technologies and advancements. While there are standardized file formats used in AM such as standard tessellation language (STL), of particular interest are improvements in cross-platform standardized CAD programs that can easily be specialized for specific printing types, materials, machines, and applications.

A significant bottleneck that is often overlooked is the need for developing software and programs that streamlines the interfacing of 3D printers and other systems involved in a manufacturer’s supply chain. This is particularly important in the medical field – for example, software that could automatically translate x-ray images from an implant into a fully-produced functional component.
Situation Analysis by Industry

Perhaps unsurprisingly due to its long history in manufacturing, this roadmap concludes that Ohio is overrepresented within the larger Additive Manufacturing marketplace in terms of both current market size and future innovation. Ohio is particularly strong in additive manufacturing based automotive, medical, and aerospace & defense manufacturing. This corresponds well with Ohio’s historical strength in these industries.

These results are highly encouraging in support of Ohio’s efforts to grow its additive manufacturing capabilities. However, these numbers only support a rosy view of Ohio’s innovation capability and do not necessarily translate into larger industry market gain. Perhaps Ohio initiatives to support AM technology transfer for industry use should be considered.

As stated in this Report’s “Methodology” section, data for OVs was compiled on the current and future locations of AM, as well as which sectors provide Ohio with the most opportunities. We compared the number of journal publications, the number of patents, and changes in market sizes for AM sectors between 2003 and 2013. We utilized both absolute and year-over-year growth as part of the final model. An equation developed for this data provided the OV for AM-based automotive, medical, and aerospace & defense manufacturing.

There was not enough data to run the standard OV formula for AM materials and AM systems industries. Even if there was enough data, the AM materials and AM systems industries are fundamentally different from the other markets as the sizes of these two industries is primarily dependent on AM penetration into the other industries. As such, the equation used for these two industries was developed from a mixture of known U.S. market values for AM materials and AM systems and OVs from the other four industries.

Overall, the data is highly encouraging in support of Ohio’s current and future efforts to grow its AM capabilities.

More information and the full equations can be found in the Appendix under “The Equation” section.
**Automotive**

Ohio currently makes up ~3.8% of the U.S. Automotive Manufacturing Industry, yet:

- ~6.8% of all AM-based Automotive U.S. Patents are from or cite Ohio
- ~25% of all AM-based Automotive Journal Articles are from or cite Ohio

**Automotive Opportunity Values for Ohio:**

<table>
<thead>
<tr>
<th>Short Term OV (0-5 Years)</th>
<th>Short Term OV (5-10 Years)</th>
<th>Overall OV (0-10 Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.4</td>
<td>9.3</td>
<td>16.7</td>
</tr>
</tbody>
</table>

The Automotive Industry has a particularly high OV in relation to the size of its industry. The this high OV number is likely in part due to Ohio’s historical and current strength in the automotive sector as a percentage of total GDP by state.

**Industry Overview**

- In 2013, the automotive industry accounted for $531M, or 17.3%, of the total AM market
- The adoption of AM in the automotive industry has been bottlenecked by
  - The need for mass-produced products
  - Limitations in printing materials.
- Widespread substitution of AM for traditional manufacturing in the automotive industry is a long-term goal
  - Once it is cost effective, the switch from traditional manufacturing to AM will be abrupt and rapid
- Uses for certain custom repair jobs, particularly for legacy components and aftermarket products, will likely see limited adoption by the marketplace before the end of the decade
- Recent advancements in AM printers has given car designers the ability to print whole car bodies for prototyping purposes

**Trending**

- Prototyping
- Repair
- Aftermarket Components
- Experimental Manufacturing
  - Engines
  - Brakes
  - Valves
Heat Exchangers
- Wheel Components
- Door Panels
- Body
- Interior Design

**Gaps and Barriers for Automotive Applications:**

**Printing Speed**
- Current speeds are too slow for mass production
- Large prints tend to require more extensive post-processing for tight tolerance requirements
- AM technology capable of printing large automotive parts is less mature, and thus less optimized and refined for speed than AM utilized for smaller applications.

**Material Types**
- Metal printing, a critical technology for automotive, is still in its infancy
- Components that impact safety have to be approved by government agencies for use
- Uncertainty regarding life expectancy and unknown structural flaws in metal-based AM components also has limited the adoption of AM
- Some limitations in metal types, though new metal-based AM technologies are rapidly solving this issue

**Cost**
- Large metal-based AM printers are expensive
- Cost of materials for AM metal production
- Lack of established large metal-based AM supply chain
Medical
Ohio currently makes up ~4.1% of the U.S. Medical Manufacturing Industry, yet:

- ~11.9% of all AM-based Medical U.S. Patents come from or cite Ohio
- ~21.9% of all AM-based Medical Journal Articles are from or cite Ohio

Opportunity Values

<table>
<thead>
<tr>
<th>Short Term OV (0-5 Years)</th>
<th>Short Term OV (5-10 Years)</th>
<th>Overall OV (0-10 Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.19</td>
<td>10.66</td>
<td>18.86</td>
</tr>
</tbody>
</table>

With the highest OV rating of any industry, the Medical Industry represents the biggest potential for AM in Ohio. The ability of AM to rapidly produce a complex, unique component tailored for a specific application makes it a perfect manufacturing method for many medical needs, which range from implants to prosthetics. Additionally, the sheer size of the medical industry, which has an inelastic demand curve and a constant push for cutting-edge technologies, make it a particularly attractive market for AM.

Industry Overview:

- Growing for medical devices and uses requiring custom (per patient) components
  - Particular promise in implants such as bone and joint replacements
- Primary bottle neck to more widespread use is the always strict government medical regulation
  - Other issues involve long term testing of such devices
- In 2014, medical/dental accounted for 13.7% of the total revenue for the AM market
- Because of some of the relatively smaller, customizable devices, AM is a great fit for the medical industry
- An estimated 20 different implantable AM products have been approved by the FDA
- A significant bottleneck that is often overlooked is the need for developing software and programs that streamlines the interfacing of 3D printers and other systems involved in a manufacturer’s supply chain

Trending

- Broken medical equipment
- Bone and joint implants
- Biological Cells (skin, tissue, organs, etc).
- Rapid Replicating of custom components based on scans
- The dental industry is transitioning to “digital dentistry” due to the scanning tools, software and AM.
• Hearing Aids
• Computed tomography (CT) scan imaging is the method of choice for replicating bone structures.
• Technique that is used for imaging in the dental field is cone-beam computed tomography (CBCT).

Gaps and Barriers for Medical Applications:

Standardization

• FDA Approval for medical devices
• No long term studies regarding safety
• Standardize Processes and manufacturing procedures
• Software
  o Multiple data formats
  o Image processing
  o Supply Chain Integration

Material Types

• Non-toxic materials, transplant rejection
• Required properties for different uses
• Purity of components
Consumer Products
Ohio currently makes up ~4.7% of the U.S. Consumer Product Industry, yet

- ~17.6% of all AM-based Consumer Product U.S. Patents come from or cite Ohio
- ~25.8% of all AM-based Consumer Product Journal Articles are from or cite Ohio

Opportunity Value

<table>
<thead>
<tr>
<th>Short Term OV (0-5 Years)</th>
<th>Short Term OV (5-10 Years)</th>
<th>Overall OV (0-10 Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.31</td>
<td>7.73</td>
<td>14.04</td>
</tr>
</tbody>
</table>

The Consumer Products Industry has a particularly high OV in relation to the size of its industry. This high OV number is likely in part due to Ohio’s historical and current strength in the consumer products sector as a percentage of total GDP by state. From 2012 to 13 there was a radical increase in journals and patents for AM. This will likely translate into an increase in market size for 3D printed consumer product components. In 2013 Ohio had 30% of all new journals and patents, a 5% increase from 2012.

Industry Overview:

- Consumer products is a rather broad industry, including, but not limited to, tools, jewelry, toys, kitchen appliances, mobile phones, home electronics, and computers
- It is valued at around $552.6M, and accounts for approximately 18% of the market share
- It had the largest market share for eight years; this designation was then held by the industrial/business machine industry
- The digital influence on the industry has allowed for many different online retailers, such as the Shapeways 3D printing marketplace and community
- Research is ongoing for more materials to be able to provide products with better surface quality and less post-processing
- Enhances products with increased geometric complexity, decreased system complexity and increased customization

Trending

- Currently manufacturing custom dolls and toys, jewelry, phone/electronic cases, etc.
- Decreasing prices for consumer 3D printers
- More money spent in branding and marketing efforts
- Increasing interest in hobbyist and home designers
- Use of multiple colors for more detailed products
- Increasing use of scanning and figure sculpture prints
- Increased demand for embedded products
• Development of polymer electronics
• Growing demand for high-performance textiles

Gaps and Barriers for Consumer Product Applications:

1) **Cost**
   • Expiring patents open doors for more processes to be applied to hobbyist and industrial printers for lower costs.
   • Materials cost makes experimenting expensive on multiple products for small businesses.
   • Services (cost to have products printed)

2) **Printing Speed**
   • Custom parts have less of a need for faster speeds, but the speeds are too slow for mass production.
   • Need of faster printers while maintaining high quality finished consumer products.

3) **Standardization**
   • Developing software that enables more components to be built inside products as they are printed.
   • Safety concern for toys - i.e. photo polymers cured by UV lights may be toxic
Aerospace and Defense
Ohio currently makes up ~2.8% of the U.S. Aerospace and Defense Industry, yet:

- **1.7%** of all AM-based Aerospace and Defense U.S. Patents come or cite Ohio
- **32.6%** of all AM-based Aerospace and Defense Journal Articles are from or cite Ohio.

This significant differentiation between journals and patents could be due to the small sample size of patents.

**Opportunity Value**

<table>
<thead>
<tr>
<th>Short Term OV (0-5 Years)</th>
<th>Short Term OV (5-10 Years)</th>
<th>Short Term OV (0-10 Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.35</td>
<td>5.58</td>
<td>9.93</td>
</tr>
</tbody>
</table>

The Aerospace and Defense Industry has a particularly low OV in relation to the size of its industry. This low OV number is likely due to economic challenges resulting in defense budget declines that indirectly impact the ability to conduct research and development in the aerospace and defense sector.

From review of the graph reflecting journals for US and Ohio we see a gradual increase up until 2011 and then nearly doubling in 2012 and 13. This will likely translate into an increase market size for 3D printed components for the aerospace and defense industry. Meanwhile, Ohio shows disproportionate totals for AM related patents for this industry. This may be a cause for concern within the model causing lowered OV values. Although we contribute some error to the sample sizes being very small, we also take into account that a combination of extremely low values can skew the results.

**Industry Overview:**

- The largest net exporter, and one of the largest contributors to our nation’s gross exports
- Contribution to the nation’s GDP is 2.23%
- The 50 largest aerospace and defense companies represent an estimated 91.8% of the total revenues in the industry.
- Has a nominal GDP contribution higher than the primary metal manufacturing industry
- States with heavy reliance and concentration of aerospace and defense employment as a percentage of total statewide activity exhibits a high industry GDP.

**Trending**

- Increasing use of lightweight structures
  - Ability to create parts with high geometric and functional complexity
Breaking current engineering and manufacturing limitations

- Customization to the aircraft interior
- More complex structures with high strength
- Noise reducing products
- Parts that will cause fuel-reduction
- Printing unmanned aircraft systems (UAS)
- Engine turbine components
- Small arms (grips, rails, body, etc.)
- Field repairs – 3D printers in forward bases for printing replacement parts on demand

Of particular Interest for Aerospace in Ohio:

- Big Area Additive Manufacturing (BAAM)
  - Technology being developed at Oak Ridge National Laboratory and commercialized by Cincinnati, Incorporated in Harrison, Ohio
  - Primary use is in the production of large tools for aerospace composites (currently up to 10 feet by 10 feet by 10 feet.)
  - Technology used to 3D print an automobile (called Strati) in 2 days
  - Prints at 500 to 1,000 times the speed of other polymer 3D printers
  - Uses plastic pellets directly (versus filaments)
  - Prints “out of the oven”
- Arburg Freeformer 3D Printer
  - Technology developed by Arburg, a German injection molding company
  - Primary use is in prototyping and mold production
  - Uses plastic pellets

Gaps and Barriers for Aerospace and Defense Applications:

1. Increase Material Types
   - A key development for direct manufacturing of parts has been to enhance the mechanical properties of resulting parts based on materials
   - Metal printing, a critical technology for aerospace, is still in its infancy
   - Components that impact safety have to be approved by government agencies for use
   - Uncertainty regarding life expectancy and unknown structural flaws in metal-based AM components also has limited its adoption
   - Some limitations in metal types, though new metal-based AM technologies are rapidly solving this issue

2. Standardization
- Promote knowledge of the industry to help stimulate research and encourage the implementation of technology
- Measure the performance of different production processes
- Ensure the quality of the end products
- Specify procedures for the calibration of additive manufacturing machines
- No long term studies regarding safety
- Software
  - Multiple data formats
  - Image processing
  - Supply Chain Integration
AM Systems
Opportunity Value

<table>
<thead>
<tr>
<th>Medical Short Term OV (0-5 Years)</th>
<th>Medical Short Term OV (5-10 Years)</th>
<th>Medical Overall OV (0-10 Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6</td>
<td>4.5</td>
<td>8.1</td>
</tr>
</tbody>
</table>

This industry is one of the smallest industries in additive manufacturing. It is encompassed in the other categories because it is the sale of the 3D printers as well as the materials. In order to calculate Opportunity Value, we took the total sum of the other categories and took 13% of that because according to Wohler’s report AM systems accounted for 13% of the Additive Manufacturing Market.

The AM systems had a great start on revenue in 2003. Overall the revenue for AM system has constantly increased except 2005 and 2010. This industry will continue to increase as consumers’ usages expand. AM systems revenue is projected to double by 2017.

Industry Overview:

- Additive Manufacturing systems are the sale and servicing of 3D printers
- 3D printer market size $1.3 (billion)
- AM systems accounted for 13% Additive Manufacturing Market
- By 2013, there were more than 23,000 commercial 3D printers machines in use
- Major AM system producers:
  - Stratasys
  - 3D Systems
  - EOS
  - SLM Solutions
  - Concept Laser
- See section “Additive Manufacturing Technologies” for list of major printing processes

Trending

- Commercial usage
- Decreasing prices for consumer 3D printers
- Smaller Desktop and Consumer grade systems
- Larger internal memory that can store the entire job, without requiring a connected computer
- Blue LED technology which can print for over 50,000 hours without a light source change
- Flip-up doors for easy user access
• Overnight printing with an automated off function
• Pause & Resume function on printers
• Stackable trays, which are space saving
• Desktop size with low noise printers

Gaps and Barriers for AM Systems Applications:

1) Patents
   • Decreased number of patents has slowed down the production and sales of the machines
2) Labor Cost
   • Increase in reliable systems will reduce effort for monitoring and troubleshooting
   • Increase in systems with automated removal of excess powder
3) Build Rate
   • Due to an online monitoring system there will be an increased process stability
   • Increase layer structure with different layer thickness
   • Enhance powder dispensing process
4) Machine prices
   • Decrease in machine prices will increase consumers purchase of 3D printer
   • Increasing process and quality control electronics will increase machine prices
AM Materials
Opportunity Value

<table>
<thead>
<tr>
<th>Medical Short Term OV (0-5 Years)</th>
<th>Medical Short Term OV (5-10 Years)</th>
<th>Medical Overall OV (0-10 Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>5.7</td>
<td>10.2</td>
</tr>
</tbody>
</table>

Industry Overview:

- In 2013 an estimated 528.8 million dollars was spent on materials for the AM systems worldwide.
- Materials account for 26% of AM revenues.
- Binder Jetting and Powder Bed Fusion processes have filaments for 75% of available materials

Trending

- Functional Materials
- Polymers approved by FDA for contact with food i.e. storage containers
- Composite and Hybrid materials
- Plastics
  - ABS - Acrylonitrile Butadiene Styrene
  - HARD PLA - Polylactic Acid
  - SOFT PLA - Polylactic acid
  - PVA - polyvinyl alcohol
  - PC – polycarbonate
- Metals
  - Aluminum alloys
  - Copper-based alloys
  - Steel
  - Stainless steel
  - Titanium
  - Gold
  - Silver

Gaps and Barriers for Consumer Product Applications:

4) Decrease Cost
- Most AM polymers are higher in cost compared to traditional manufacturing with thermoplastics and photopolymers ranging from $170-$250 per kilogram compared to $2-$3 per kilogram.
5) **Increasing Material Types**
   - R&D for more functional filaments.
   - Materials that meet standards and regulations.

6) **Education**
   - Knowledge of material types and properties
   - Knowledge of correct materials for the processes
Action Plan

The following policy/initiatives/concepts have been provided by this report’s authors’ in response to OMI’s request for recommendations on activities and suggested approaches that can be undertaken to overcome the gaps/barriers that hinder more widespread adoption of AM.

As stated in this market study (pages 14-19), almost every AM gap/barrier falls under one of five categories. For the purpose of approach/policy, we suggest prioritizing initiatives that focus on the following in order of most to least importance:

1. Cost
2. Production Speed
3. Standardization
4. Material Types
5. Education

Perhaps a few more specific themes to consider while making policy include:

1. The broad range of materials now printable and the natural progression of such technology suggest that the AM market has reached the point in which additional government support for material research will have a decrease impact on the growth of AM as compared to five years ago. Instead, supporting initiatives that look to improve printing processes (cheaper, faster, efficient) provided a much greater benefit for the future widespread adoption of AM.
2. Clear government safety standards, particularly for medical applications, will be critical for the expansion of AM for medical uses.
3. While growing, the use of AM is still almost insignificant in comparison to traditional manufacturing methods, and despite a history reaching back to the 1980’s, it is still struggling to breach the barrier between niche uses and mainstream production. While education and outreach on the potential of AM is important, widespread penetration will only occur after the technology proves itself to be cost effective.
4. Tax breaks, grants, and other long term incentives for Ohio manufacturing companies who utilize AM processes in their business may promote early adoption. Previous government resources have tended to focus on having access to AM printers and services. The issue with this approach is that many manufacturers have experimented with AM, but many of these producers, particularly small to medium size businesses, have not integrated AM into their supply chain as a core manufacturing process.

Perhaps another approach is to specifically tailor incentives and resources towards helping manufacturers increase profit margins within their core business by adopting AM for certain critical needs already being completed via traditional manufacturing methods. By utilizing AM in their core business, Ohio manufacturers would gain experience using the technology.
within a business environment with the natural side effect of promoting AM innovation to maintain their competitive advantage.
Appendices

Other AM Industries of Interest

The following industries are/will integrate AM for various applications, and may be disruptive after. The widespread adoption of AM for electronics and clothing is likely still over a decade away and thus falls outside the current timeline of this report, while food represents a niche market outside the confines of the most promising industries named in this report.

Electronics

AM offer a huge array of benefits for electronics allowing for more customized and optimized circuits designed and printed for specific applications. One of the biggest breakthroughs however, would be the ability to commercially print computer processors and to a lesser extent circuit boards. The layering method that 3D printing inherently uses would allow 3D chip stacking (printing processing cores on top of each other). Stacking processors allows for exponential increases in processing power and decrease in energy usage, and would arguably be one of the biggest innovations in chip designs since the development of the transistor. Stacking circuits on a circuit board also will allow substantial miniaturization of electronic components.

However, 3D printing of electronics is very underdeveloped as compared to other 3D printing technologies. While there has been some success, and at least one company has developed a printer that can print certain circuits, its use in widespread production of integrated circuits at the nanometer level is still far in the future. The first uses for AM in electronics will likely be prototyping electronic components, eventually transitioning to production.

Clothing

Fashion Designers have been experimenting with everything from printing gold jewelry to dresses. However, due to the difficulty in printing non-rigid materials, these clothes generally require hundreds of small hinges to simulate the flexibility of cloth.

Printing shoes will likely be the first widely printed clothing, and designers have printed slippers and high-heel style shoes. Besides the ability to print interesting geometric shapes, the ability to custom print a shoe specifically tailored for individual customers offers tremendous value. While not likely within the next decade, it is very much possible that shoe stores will utilize a series of 3D printers where customers can buy custom printed shoes on-demand.

Perhaps by 2030, it is very possible that custom AM clothing will be common with a production chain similar to the shoe example above.

Food
There is currently a niche market for 3D printed high-end chocolates and other candies via extrusion based printers. The major current benefit of using 3D printers in food is esthetic – interesting custom designs and structures not normally viable via traditional manufacturing methods. While perhaps not a huge market, many cultures internationally place a very high value on esthetics in food with countries such as Japan being famous for it. As such, there may be larger market opportunities regarding overseas exports.
The Opportunity Value Equation
The following equation represents our anticipated model that produces a standardized opportunity value based on collected data:

For (0 – 5 yr) anticipated opportunity value we obtain our value by taking the square root of the following equation for each individual industry. The equation is broken down into three primary sections:

1st: Computing anticipated market weight

$$\sqrt{\text{Total Market Revenue (2003 – 2013)} \times \text{avg AM\% of Industry (2003 – 2013)} \times \left[ \text{avg GR\% (2004 – 2007)} + \text{avg GR\% (2010 – 2013)} + \text{Change in rates} \right]}$$

2nd: Computing anticipated patent weight

$$\sqrt{\text{Total US Patents (2003 – 2013)} \times \text{avg OH\% of Patents (2003 – 2013)} \times \left[ \text{avg GR\% (2004 – 2007)} + \text{avg GR\% (2010 – 2013)} + \text{Change in rates} \right]}$$

3rd: Computing anticipated journal weight

$$\sqrt{\text{Total US journals (2003 – 2013)} \times \text{avg OH\% of journals (2003 – 2013)} \times \left[ \text{avg GR\% (2004 – 2007)} + \text{avg GR\% (2010 – 2013)} + \text{Change in rates} \right]}$$

The equation can more simply be summarized as:

1. Estimated total size of Ohio AM market (2003-2013)
2. Average growth rates for market (2004-07) and (2010-13)
3. Changes in consumption growth rates from 2004-07 and 2010-13
4. Estimated total journal publications for Ohio AM (2003-2013)
5. Average growth rates for journals (2004-07) and (2010-13)
7. Estimated total patents
8. Average growth rates for patents (2004-07) and (2010-13)

These values are used to give a weight to each section for the six industries being observed for (0-5 years). This method allows for the equation to be used to compare possible areas of opportunity for additive manufacturing in Ohio in any industry given its usage is applicable. While this model uses arbitrary values to calculate the opportunity for future R&D in various
industries, there are still significant problems with calculating market sizes, total patents (actual) and total journals (actual) sizes for additive manufacturing.

It is assumed in the model that the anticipated growth for the next 0-5 years will reflect that of the trends observed in average growth rates from 2003-2013. For the following 5-10 years, the second model suggests rapid increases in growth rates can characterize the field expanding in the ladder years.

For (5 – 10 yr) anticipated opportunity value, we obtain our value by taking the square root of the following equation for each individual industry. The equation is broken down into three primary sections:

1st: Computing anticipated market weight

\[
\left(\sqrt{\text{Total Market Revenue} \times \text{avg AM\% of Industry} \times \text{avg AM\% of Industry}} \times \text{max GR\% (2004 – 2007) + max GR\% (2010 – 2013) + Change in rates}\right) +
\]

2nd: Computing anticipated patent weight

\[
\left(\sqrt{\text{Total US Patents} \times \text{avg OH\% of Patents} \times \text{max GR\% (2004 – 2007) + max GR\% (2010 – 2013) + Change in rates}} \right) +
\]

3rd: Computing anticipated journal weight

\[
\left(\sqrt{\text{Total US journals} \times \text{avg OH\% of journals} \times \text{max GR\% (2004 – 2007) + max GR\% (2010 – 2013) + Change in rates}} \right)
\]

The equation can more simply be summarized as:

1. Estimated total size of Ohio AM market (2003-2013)
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3. Changes in consumption max growth rates from 2004-07 and 2010-13
4. Estimated total journal publications for Ohio AM (2003-2013)
5. Maximum growth rate for journals (2004-07) and (2010-13)
7. Estimated total patents
8. Maximum growth rate for patents (2004-07) and (2010-13)
*Note: Square roots are used for normalization and weighting purposes.
### Automotive Market Size in Billions

<table>
<thead>
<tr>
<th>Years</th>
<th>USA</th>
<th>Growth Rate</th>
<th>Ohio</th>
<th>Growth Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>$357.04</td>
<td>---</td>
<td>$13.39</td>
<td>---</td>
</tr>
<tr>
<td>2004</td>
<td>$392.08</td>
<td>9.81%</td>
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<td>9.19%</td>
</tr>
<tr>
<td>2005</td>
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</tr>
<tr>
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<tr>
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<tr>
<td>2012</td>
<td>$442.10</td>
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<td>2.05%</td>
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</table>

### Additive Manufacturing related Automotive Patents

<table>
<thead>
<tr>
<th>Years</th>
<th>USA</th>
<th>Growth Rate</th>
<th>Ohio</th>
<th>Growth Rate</th>
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</thead>
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<td>0%</td>
<td>1</td>
<td>---</td>
</tr>
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<td>$512.97</td>
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</tr>
<tr>
<td>2007</td>
<td>$14,824.62</td>
<td>1.45%</td>
<td>$508.67</td>
<td>-0.84%</td>
</tr>
<tr>
<td>2008</td>
<td>$14,728.95</td>
<td>-0.65%</td>
<td>$500.87</td>
<td>-1.53%</td>
</tr>
<tr>
<td>2009</td>
<td>$14,328.01</td>
<td>-2.72%</td>
<td>$476.17</td>
<td>-4.93%</td>
</tr>
<tr>
<td>2010</td>
<td>$14,639.75</td>
<td>2.18%</td>
<td>$488.56</td>
<td>2.60%</td>
</tr>
<tr>
<td>2011</td>
<td>$14,868.84</td>
<td>1.56%</td>
<td>$501.34</td>
<td>2.62%</td>
</tr>
<tr>
<td>2012</td>
<td>$15,245.91</td>
<td>2.54%</td>
<td>$517.06</td>
<td>3.14%</td>
</tr>
</tbody>
</table>

### Total Manufacturing Gross Domestic Product

<table>
<thead>
<tr>
<th>Years</th>
<th>USA</th>
<th>Growth Rate</th>
<th>OH</th>
<th>Growth Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>$1,641.50</td>
<td>---</td>
<td>$91.86</td>
<td>---</td>
</tr>
<tr>
<td>2004</td>
<td>$1,737.49</td>
<td>5.85%</td>
<td>$97.26</td>
<td>5.88%</td>
</tr>
<tr>
<td>2005</td>
<td>$1,785.79</td>
<td>2.78%</td>
<td>$97.93</td>
<td>0.69%</td>
</tr>
<tr>
<td>2006</td>
<td>$1,878.72</td>
<td>5.20%</td>
<td>$98.95</td>
<td>1.04%</td>
</tr>
<tr>
<td>2007</td>
<td>$1,941.01</td>
<td>3.32%</td>
<td>$98.96</td>
<td>0.01%</td>
</tr>
<tr>
<td>2008</td>
<td>$1,863.61</td>
<td>-3.99%</td>
<td>$89.90</td>
<td>-9.16%</td>
</tr>
<tr>
<td>2009</td>
<td>$1,718.64</td>
<td>-7.78%</td>
<td>$75.76</td>
<td>-15.73%</td>
</tr>
<tr>
<td>2010</td>
<td>$1,835.00</td>
<td>6.77%</td>
<td>$82.10</td>
<td>8.37%</td>
</tr>
<tr>
<td>2011</td>
<td>$1,848.02</td>
<td>0.71%</td>
<td>$88.74</td>
<td>8.09%</td>
</tr>
<tr>
<td>2012</td>
<td>$1,882.24</td>
<td>1.85%</td>
<td>$89.49</td>
<td>0.85%</td>
</tr>
<tr>
<td>2013</td>
<td>$1,939.67</td>
<td>3.05%</td>
<td>$92.34</td>
<td>3.18%</td>
</tr>
</tbody>
</table>
Ohio Additive Manufacturers, Organizations, and Initiatives
The following information specific to Ohio was synthesized primarily from the 2014 Wohlers Report (www.wohlersassociates.com/2014report.htm), America Makes (americamakes.us), and additional research:

- **3D Systems** acquired polymer filament producer *Village Plastics* based in Norton.
- *Oak Ridge National Laboratories* teamed with machine tool manufacturer *Cincinnati Inc.* to develop faster polymer AM material extrusion system.
- *Amazon* choose Cincinnati 3D AM manufacturer 3DLT to be part of pilot program to sell 3D-printed items on Amazon.
- Columbus based *Fabrisonic, LLC* manufactures UAM printers – a process for printing metal based components.
- Columbus based *EWI* established the Additive Manufacturing Consortium (AMC) in 2010 to advance manufacturing readiness in metal printing technology.
  - IC3D
  - Fabrisonic
- Miamisburg based Mound Laser & Photonics Center received funding to further develop metal powder bed fusion.
- Ohio State University has appointed its first AM engineering chair to support AM education.
- University of Akron based *Advanced Additive Manufacturing Lab* conducts significant AM basic and applied research.
- *America Makes* in Youngstown supports the collaboration of over 100 AM organizations and companies across the country.
- *General Electric* is doing significant research in AM for use in aircraft engine components.
- *Applied Optimization* in Dayton uses AM in various aerospace engineering projects.
- Canton based *Timken* has been supporting AM research both internally and with the *University of Akron*.
- *Bastech*, a Dayton based manufacturer, specializes in AM components and services.
- *NorTech* in Cleveland specializes in supporting innovation in emerging technologies including AM.
- *Rp+m*, a Avon Lake based manufacturer, specializes in AM components and services.
- Materials Park based *ASM International* is the world’s largest association metals-centric engineer and scientists with many members being involved in metal-based AM.
- University of Dayton Research Institute – Multiscale Composites and Polymers Division, Stratasys, RP+M, PolyOne, and aerospace OEMs have formed a primer research and development team designing new polymer systems for the next generation of AM printers.
Roadmap Contributors

FASTLANE and the University of Dayton Research Institute have extensive experience in Additive Manufacturing initiatives for the public and private sectors. Additionally, UDRI has an established and dedicated veteran market analysis team who has worked on projects ranging from analyzing research and development market opportunities to feasibility studies for foreign technology transfer for private industry customers. This analyst team, consisting of a mixture of professionals and graduate students, has worked closely on this Roadmap with FASTLANE’s manufacturing professionals, UDRI AM researchers, and AM entities in the private sector.

FASTLANE

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  University of Dayton Research Institute

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- **UDRI Authors:** Keyonna Sturdivant, Joseph Battle, Yacouba Yeye, Melody Wilson

Special thanks to Thomas Hughes of PolyOne Corporation for additional expert input