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Additive Manufacturing: A Summary of the Literature

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College of Urban Affairs
Center for Economic Development

Prepared for:
Ohio Manufacturing Institute

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April 2015

**ADDITIVE
MANUFACTURING: A
SUMMARY OF THE
LITERATURE**

**CENTER FOR
ECONOMIC
DEVELOPMENT**

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ABOUT THIS REPORT

The Center for Economic Development at the Levin College of Urban Affairs at Cleveland State University prepared this report for the Ohio Manufacturing Institute (OMI) at The Ohio State University. The objective of this study is to provide background analysis of additive manufacturing (AM) for the OMI as they prepare a roadmap for the future and recommendations on AM for the Ohio Development Services Agency (ODSA).¹ This report is a literature review and summary of findings.

Literature on AM was collected from various sources. Academic articles, reports, and studies were collated and analyzed from databases, internet searches, and publications. The goal of this report is to provide a clear context of the state, national, and international conversation on AM, as well as delineate opportunities and challenges as it relates to this technology.

It is important to note two major considerations in this literature review: the designation between AM and 3D printing, and overall technical specifications: (1) AM is known in the mainstream media as “3D printing,” but in actuality, this designation is a subset of the AM concept. On occasion, this report will single out 3D printing technology as a subset of AM. There is a vast amount of material on 3D printing because it is currently a popular subject for the media. At times, the literature refers to 3D printing separately from AM, and it is unknown to the authors of this report whether these different designations are deliberate. To avoid confusion, we use both concepts and report the labeling as the literature refers to it. This provides clarity for the reader. (2) There is a significant amount of technical information in the AM literature that is not covered in this report. This report is designed only to consider AM in the context of the overall conversation. No technical information, mathematics, or other technical concepts involved in the AM conversation will be covered.

¹ This report was prepared with financial support from the State of Ohio. All contents of this report reflect the views of the Grantee and do not reflect the views of ODSA or that of the State of Ohio.

INTRODUCTION

DEFINITION

Additive manufacturing is known as the “third industrial revolution” because of its potential to change the manufacturing market.² Additive manufacturing (AM) is a manufacturing process where material is added layer-by-layer to create a product.³ American Society for Testing and Materials (ASTM) International Committee F42 on AM technologies defines AM as the “process of joining materials to make objects from three-dimensional (3D) model data, usually layer by layer, as opposed to subtractive manufacturing methodologies.”⁴ Traditional manufacturing, a.k.a. subtractive manufacturing, is a process where parts are made, stamped, or molded from larger pieces of materials.

AM is known in the mainstream media as “3D printing,” but in actuality, this designation is a subset of the AM concept.⁵ In all, there are seven types of AM established by ASTM under the Standard Terminology for Additive Manufacturing Technologies. The seven types of AM and their aliases are:⁶

- 1) Binder jetting (3D printing) –AM process where a liquid bonding agent is deposited to join powdered materials together.
- 2) Direct energy deposition (direct manufacturing) –AM process where thermal energy fuses or melts materials together as they are added.
- 3) Material extrusion (fused deposition modeling) – AM process that allows for depositing material via a nozzle.
- 4) Material jetting - AM process where droplets of material are deposited.
- 5) Powder bed fusion (laser sintering) – AM process where thermal energy fuses or melts material from a powder bed.
- 6) Sheet welding (e-beam welding, laminated object manufacturing) - AM process where sheets of materials are bonded together.
- 7) Vat photo-polymerization (digital light processing) - AM process where liquid photopolymer in vat is cured by light.

² Huang, Y. & Leu, M.C. (2014, March). *Frontiers of Additive Manufacturing Research and Education: Report of NSF Additive Manufacturing Workshop*. Gainesville, FL: University of Florida Center for Manufacturing Innovation.

³ Ford, S. (2014, September). Additive Manufacturing Technology: Potential Implications for U.S. Manufacturing Competitiveness. *Journal of International Commerce and Economics*.

⁴ Huang, Y., Leu, M.C., Mazmunder, J., & Donmez, A. (2015). Additive Manufacturing: Current Sate, Future Potential, Gaps, Needs, and Recommendations. *Journal of Manufacturing Science and Engineering* 137, 014001-1-014001-10

⁵ Webber, C. L., Pena, V., Micali, M. K., Yglasias, E., Rood, S. A., Scott, J. A., & Lal, B. (2013). *The Role of the National Science Foundation in the Origin and Evolution of Additive Manufacturing in the United States*. Washington, D.C.: IDA Science and Technology. IDA Paper P-5091

⁶ Ibid.

INDUSTRY TRENDS

- Much of the innovation taking place in the AM market is in the private sector, especially regarding patents.⁷
- Rapid prototyping is the most cited benefit and use of AM, but the applications far exceed this sole use. A report in 2009 creating a roadmap for the future of AM showed 15 uses, industries, and applications including: architecture, aeronautical, aerospace, art, automotive, consumer products, education, electronics, energy, entertainment, medical, nanotechnologies, repair, tooling, and visualization.⁸
- AM can be useful in remote locations where parts need to be created and access to the site is difficult to traverse.⁹
- The companies with the largest AM machine sales (in descending order) through 2011 are:¹⁰

1. Stratasys (USA)	12. Makerbot (USA)
2. Z Corporation (USA)	13. Objet (Israel)
3. Bits from Bytes (UK)	14. Solidscape (USA)
4. 3D Systems (USA)	15. Envisiontec (Germany)
5. Makerbot (USA)	16. EOS (Germany)
6. Objet (Israel)	17. Beijing Yinhuo (China)
7. Solidscape (USA)	18. Solido (Israel)
8. Stratasys (USA)	19. DWS (Italy)
9. Z Corporation (USA)	20. DTM (USA)
10. Bits from Bytes (UK)	21. Helisys (USA)
11. 3D Systems (USA)	

2009 NATIONAL ROADMAP

In 2009, 65 individuals attended The Roadmap for Additive Manufacturing (RAM) Workshop in Alexandria, VA to develop a roadmap for the next 10-12 years of the technology.¹¹ Attendees included individuals from universities, industry and the U.S. government (NSF, ONR, DARPA, NIST, NIST, MEP, NIH, AFRL, and NASA). Out of this workshop, 8 main recommendation topics surfaced:

1. Design
2. Process Modeling and Control
3. Materials, Processes and Machines
4. Biomedical Applications
5. Energy and Sustainability Applications
6. Education
7. Development and Community
8. National Testbed Center

⁷ Webber, C. L., Pena, V., Micali, M. K., Yglasias, E., Rood, S. A., Scott, J. A., & Lal, B. (2013). *The Role of the National Science Foundation in the Origin and Evolution of Additive Manufacturing in the United States*. Washington, D.C.: IDA Science and Technology. IDA Paper P-5091

⁸ Bourell, D. L., Leu, M. C., Rosen, D. W. (2009). *Roadmap for Additive Manufacturing Identifying the Future of Freeform Processing*. Austin, TX: The University of Texas at Austin

⁹ Solid Print: Making Things with a 3D Printer Changes the Rules of Manufacturing. (2012, April). *The Economist*. www.economist.com/node/21552892

¹⁰ Ibid.

¹¹ Bourell, D. L., Leu, M. C., Rosen, D. W. (2009). *Roadmap for Additive Manufacturing Identifying the Future of Freeform Processing*. Austin, TX: The University of Texas at Austin

Much of what is reported in the 2009 report laid the groundwork for the broader conversation within the engineering and AM community. The issues listed above are addressed in many different ways in this literature review. The legacy and integrity of the 2009 roadmap shows the strength of the document, as well as the persistent problems that are still prominent years later.

AM OPPORTUNITIES

Overall, studies cite three major benefits and opportunities that AM can provide:

1. Prototyping and reduced time to market
2. Innovation
3. Business case for widespread application

PROTOTYPING & REDUCING TIME TO MARKET

- AM has been a game changer for rapid prototyping. AM allows companies to change design on the fly in a just a few hours, as opposed to the traditional method of creating a prototype from wood or metal from machine shops.¹²
- AM can contribute to entrepreneurial success because entrepreneurs can have a low cost mechanism to produce a prototype.¹³
- Rapid prototyping is the vast majority of 3D printing users.¹⁴

INNOVATION

- AM spurs innovation because it allows users to manufacture complex structures quickly and efficiently.¹⁵
- There is conjecture that 4D printers are being built to incorporate “shape memory fibers” into inks to create different forms.¹⁶
- Price Waterhouse Cooper (PWC) has conducted a survey of manufacturers that shows small firms are keeping pace with large firms in the adoption of 3D printing.¹⁷
- Conversation has begun about how universities and industry can collaborate on this technology through technology transfer, but collaboration seems to be limited to federally funded programs (i.e. SBIR/STTR, NSF).¹⁸
- There is significant amount of funding in AM. Grants can be provided under:
 - SBIR/STTR
 - Federal Agencies: NSF, DoD, DOE
 - Center for Aerospace Manufacturing Technologies (CAMT)
 - National Additive Manufacturing Innovation Institute (NAMII)

¹² Bradshaw, B. (2011, May 1). 3-D Printing Provides New Options for Prototyping, Moldmaking. *Moldmaking Technology*. Retrieved March 30, 2015 from <http://www.moldmakingtechnology.com/articles/3-d-printing-provides-new-options-for-prototyping-moldmaking>

¹³ A Spin on Additive Manufacturing. (2013, September 17) *Modern Machine Shop*. Retrieved March 10, 2015 from <http://www.mmsonline.com/articles/a-spin-on-additive-manufacturing>

¹⁴ Price Waterhouse Cooper (2014). *3D Printing and the New Shape of Industrial Manufacturing*.

¹⁵ Huang, Y., Leu, M.C., Mazmunder, J., & Donmez, A. (2015). Additive Manufacturing: Current Sate, Future Potential, Gaps, Needs, and Recommendations. *Journal of Manufacturing Science and Engineering* 137, 014001-1-014001-10

¹⁶ Price Waterhouse Cooper (2014). *3D Printing and the New Shape of Industrial Manufacturing*.

¹⁷ Ibid.

¹⁸ Huang, Y. & Leu., M.C. (2014, March). *Frontiers of Additive Manufacturing Research and Education*. Gainesville, FL: University of Florida Center for Manufacturing Innovation

BUSINESS CASE FOR WIDESPREAD APPLICATION

Costs Savings

- There is a significant amount of academic literature of the cost savings attributed to AM. An excellent review of this literature can be found in Thomas and Gilbert (2014).¹⁹
 - It is more cost effective to use AM built aerospace parts.²⁰
 - AM of metal parts, combined with part redesign, can show significant cost savings.²¹
 - The field is starting to consider the implication of electricity consumption in AM production as a component of the cost savings.^{22,23}
- A 2013 article by Huang, Liu, Mokasdar, and Hou examined the societal impact of AM. The positive impacts of AM included: customizable healthcare products, reduced environmental impact (reduced energy use and reduced material use), simplified supply-chain. The authors call for more research on the cost savings due to energy reduction since this is a major cost for manufactures.²⁴
- As manufactures can create products on demand with AM, the amount of inventory they need to keep on hand decreases. Inventory decreases come from the ability to manufacture needed parts on demand. Inventory costs are a significant portion of manufacturers' costs. Moreover, in traditional manufacturing if a manufacturer does not have a part in inventory, they have to order the part and this can delay production. AM can reduce these issues and costs.^{25, 26}
- Business cost savings can be achieved using AM because it can reduce the amount of transportation of parts with traditional manufacturing.²⁷
- As the technology improves, the quality of AM machines will increase, while the cost will go down.²⁸
- AM equipment has followed the digital technology progress model in which more capable and cheaper machines are introduced each year, following Moore's Law.^{29,30}

¹⁹ Thomas, D. S., Gilbert, S. W. (2014, December). Costs and Cost Effectiveness of Additive Manufacturing: A Literature Review and Discussion. *NIST Special Publication 1176*. Retrieved on March 31, 2015 from <http://dx.doi.org/10.6028/NIST.SP.1176>

²⁰ Allen, J. (2006). "An Investigation into the Comparative Costs of Additive Manufacture vs. Machine from Solid for Aero Engine Parts." In *Cost Effective Manufacture via Net-Shape Processing*, 17-1 – 17-10. Meeting Proceedings RTO-MP-AVT-139. Paper 17. DTIC Document.

²¹ Atzeni, E. & Salmi, A. (2012). Economics of Additive Manufacturing for End-Usable Metal Parts. *The International Journal of Advanced Manufacturing Technology* 62 (9-12): 1147–55.

²² Baumers, M., C. Tuck, R. Hague, I. Ashcroft, and R. Wildman. 2010. "A Comparative Study of Metallic Additive Manufacturing Power Consumption." In *21st Annual International Solid Freeform Fabrication Symposium—An Additive Manufacturing Conference, Austin/TX/USA, 9th–11th August*. Austin, TX.

²³ Baumers, M., C. Tuck, R. Wildman, I. Ashcroft, and R. Hague. 2011. "Energy Inputs to Additive Manufacturing: Does Capacity Utilization Matter?" In *22nd Annual International Solid Freeform Fabrication Symposium—An Additive Manufacturing Conference, Austin/TX/USA, 8th–10th August*.

²⁴ Huang, S., Liu, P., Mokasdar, A., & Hou, L. (2013). Additive Manufacturing and its Societal Impact: a Literature Review. *The International Journal of Advanced Manufacturing Technology*. 67 (5-8), 1191-1203.

²⁵ Walter, M., Holmstrom, J., Yrjola, H., (2004). *Rapid manufacturing and its Impact on Supply Chain Management*. Logistics Research Network Annual Conference, September 9-10, 2004, Dublin, Ireland

²⁶ Piazza, M.C., Hill, E. & Schnoke, M. (2014). *Machining Industry: Survey & Focus Groups*. Cleveland, OH: Cleveland State University.

²⁷ Thomas, D. S., Gilbert, S. W. (2014, December). Costs and Cost Effectiveness of Additive Manufacturing: A Literature Review and Discussion. *NIST Special Publication 1176*. Retrieved on March 31, 2015 from <http://dx.doi.org/10.6028/NIST.SP.1176>

²⁸ Dollar, A. M. (n.d.) *Additive Manufacturing: State of the Art and Practical Design Notes*. New Haven, CT: Yale University

²⁹ Khajavi, S. H., Partanen, J., & Holmstrom, J. (2013). Additive Manufacturing in the Spare Parts Supply Chain. *Computers in Industry*. In Press. Retrieved March 10, 2015 from <http://dx.doi.org/10.1016/j.compind.2013.07.008>

³⁰ Mack, C. (2015, March 30). The Multiple Lives of Moore's Law. *IEEE Spectrum*. Retrieved March 30, 2015 from <http://spectrum.ieee.org/semiconductors/processors/the-multiple-lives-of-moores-law>

New Markets

- There is significant discussion about technology advancements and innovation that takes place with AM, but little discussion on potential businesses and profits that can be made from this technology. It is estimated that there are seven areas of revenue streams from this technology:³¹
 1. System – creating standard and customized AM systems
 2. Services – maintaining AM systems, parts, and consumables
 3. Licenses – Licensing technology to other parties
 4. Training and Seminars – training and seminars on AM technology, design, and use
 5. Powder – sales of metal powder (some AM processes require material in powder form)
 6. Application Design – support in developing applications, and consulting on readiness
 7. Software – add-on and process software
- Currently, metal powders, used in AM, are up to 30 times more expensive than their bulk counterparts; as the volume demand for metal powder increases, the price will decrease.³² It is estimated that over the next few years the rate and speed of building products will increase while powder rates will decrease.³³
- Some researchers have suggested that examining how AM can fit into the lifecycle costs of components and create cost advantages is the best way to sell the technology.³⁴
- AM is also starting to be used in the consumer market. Products such as home electronics, entertainment components, computer and mobile device parts, shoes and fashion accessories, and customizable consumer products can use AM to create intricate designs or make it customizable.³⁵

AM CHALLENGES

AM is considered an exciting technology within manufacturing and receives attention in the popular press, but many wonder if the technology can “cross the chasm” and become adopted in all industries.³⁶ The AM value chain can be described in five areas: 1) materials, 2) systems, 3) software, 4) application of design, and 5) production.³⁷ Although all of these areas help in the creation and functioning of AM technologies, the market is fragmented with only a few key players in each area.³⁸ Moreover, overall market penetration of AM is not very large (only about 1%) and the company’s size limit investment in R&D indicates that one player cannot be active in all areas (Services, Licenses, Training and Seminars, Powder, Application Design, and Software).³⁹

³¹ Berger, R. (2013, November). *Additive Manufacturing: A Game Changer for the Manufacturing Industry?* Presentation in Munich, Germany.

³² Price Waterhouse Cooper. (2013). *3D Printing: A Potential Game Changer for Aerospace and Defense. Gaining Altitude, 7*. Retrieved on March 12, 2015 from www.pwc.com/us/gainingaltitude

³³ Berger, R. (2013, November). *Additive Manufacturing: A Game Changer for the Manufacturing Industry?* Presentation in Munich, Germany.

³⁴ Lindemann, C., Jahnke, U., Moi, M., & Koch, R. (2012). *Analyzing Product Lifecycle Costs for a Better Understanding of Cost Drivers in Additive Manufacturing*. Paderborn, Germany: Direct Manufacturing Research Center (DMRC), University of Paderborn.

³⁵ Kendrick, A. (n.d.) *3D Printing: The Next Industrial Revolution?* Tolland, CT: Nerac Inc.

³⁶ Price Waterhouse Cooper. (2013). *3D Printing: A Potential Game Changer for Aerospace and Defense. Gaining Altitude. Issue 7*. Retrieved on March 12, 2015 from www.pwc.com/us/gainingaltitude

³⁷ Berger, R. (2013, November). *Additive Manufacturing: A Game Changer for the Manufacturing Industry?* Presentation in Munich, Germany.

³⁸ Ibid.

³⁹ Ibid.

There are several challenges in widespread adoption of AM:^{40,41}

1. Bias toward conventional manufacturing
 - AM has been used for prototyping for years, but the technology is now being used to directly manufacture products in small batches.⁴²
 - PWC calls the road from using AM for prototyping to direct manufacturing the “long mile.” Most manufacturers see AM as a tool for prototyping and small batch manufacturing, but not for large production runs.⁴³
2. Economic/cost difficulties:
 - High capital and material costs
 - Most parts are optimized for conventional manufacturing
 - How cost savings can be actualized through materials and assembly
 - Necessary improvements in AM product performance
 - Supply chain geared toward traditional manufacturing
3. Intellectual Property:
 - IP protection is important to recuperate investments made in the development of AM technologies
 - Estimates indicate that IP losses due to 3D printing will reach \$100 billion by 2018.⁴⁴
 - IP is considered a major issue since the marginal cost of 3D printing is significant.⁴⁵
4. Educational challenges:
 - AM is a multidisciplinary area, therefore it is difficult to train the workforce because technologies involve a variety of disciplines (modeling, physics, metallurgy, and statistics).
 - Difficult for one person to have adequate expertise in all areas to understand technology development
5. Materials capacity

Much of the literature about the challenges regarding materials and standards in AM will be discussed below.

⁴⁰ Energetics Inc. (2013). *Measurement Science Roadmap for Metal-Based Additive Manufacturing: Workshop Summary Report*. National Institute of Standards and Technology.

⁴¹ Openshaw, E. & Cotteleer, M. (2014, June 24). 3D Printing: A Powerful Technology, but No Panacea. *Financial Times*.

⁴² Huang, Y., Leu, M.C., Mazmunder, J., & Donmez, A. (2015). Additive Manufacturing: Current Sate, Future Potential, Gaps, Needs, and Recommendations. *Journal of Manufacturing Science and Engineering* 137, 014001-1-014001-10

⁴³ Price Waterhouse Cooper (2014). *3D Printing and the New Shape of Industrial Manufacturing*.

⁴⁴ Gartner: *3D printing to result in \$100 billion IP losses per year*. (2013, October 14). Retrieved March 26, 2015 from <http://www.3ders.org/articles/20131014-gartner-3d-printing-to-result-in-100-billion-ip-losses-per-year.html>

⁴⁵ Price Waterhouse Cooper. (2013). 3D Printing: A Potential Game Changer for Aerospace and Defense. *Gaining Altitude*, 7. Retrieved on March 12, 2015 from www.pwc.com/us/gainingaltitude

MATERIALS

- One of the biggest challenges to widespread adoption of AM is the small amount of materials (e.g., polymers, metals, and ceramics) that can be used to fabricate items.⁴⁶
- Every year new materials are advanced in AM, resulting in better microstructures, and enhanced material tolerability.⁴⁷
- The types of materials used in AM (for more technical information (see Guo & Leu (2013):
 - **Polymers** are the most widely used material in AM. Most notably, nylon is the most widely used polymer because it melts and bonds better than other polymers.⁴⁸
 - **Metal** products can be formed in a “direct” way – by melting metal particles together or an “indirect” way – by bonding the metal with post-processing. There are many ways and AM methods to form metals through the indirect or direct way.⁴⁹
 - **Ceramics** are used in AM processing because of their chemical structures and resistance to high temperatures. Unfortunately, these materials can be brittle making them difficult to manufacture especially if complex geometries are involved. Examples of ceramics include, alumina, silica and zirconia. Ceramics can be produced through indirect or direct process.⁵⁰
 - **Composites** are, as their name suggests, materials that are combinations of two or more materials, either naturally (in nature) or engineered. Composites can be mixed uniformly or non-uniformly to make different compounds.⁵¹
 - **Functionally graded materials** can be created through AM processing. Guo & Leu (2013) show that, “One example is a pulley that contains more carbide near the hub and rim to make it harder and more wear resistant, and less carbide in other areas to increase compliance.” (p. 224)⁵²
- To better understand and use advanced materials in AM processes, it is suggested that research in the following areas be conducted:⁵³
 - Understand the basic physics and chemistry of AM processes
 - Develop processes based on scalable material methods
 - Develop machine modules that can be reconfigured
 - Investigate why some materials can be used in AM and others cannot
 - Develop better tools for micro- and nano- AM to build items atom by atom
 - Develop sustainable materials
- Other challenges in AM include understanding the fundamentals of materials, processes, and applications. For example, some scientists are grappling with the physics behind AM, while others question why certain materials can be used in AM and not others.⁵⁴

⁴⁶ Guo, N. & Leu, M.C. (2013). Additive manufacturing: technology, applications and research needs. *Frontiers in Mechanical Engineering*. 8(3), 215-243.

⁴⁷ Aliakbari, M. (2012). *Additive Manufacturing: State-of-the-Art, Capabilities, and Sample Applications with Cost Analysis*. Master’s Thesis: KTH, Sweden

⁴⁸ Guo, N. & Leu, M.C. (2013). Additive manufacturing: technology, applications and research needs. *Frontiers in Mechanical Engineering*. 8(3), 215-243.

⁴⁹ Ibid

⁵⁰ Guo, N. & Leu, M.C. (2013). Additive manufacturing: technology, applications and research needs. *Frontiers in Mechanical Engineering*. 8(3), 215-243.

⁵¹ Ibid.

⁵² Ibid.

⁵³ Ibid.

⁵⁴ Bourell, D.L., Beaman, J.J., Leu, M.C., & Rosen, D.W. (2009). *A Brief History of Additive Manufacturing and the 2009 Roadmap for Additive Manufacturing: Looking Back and Looking Ahead*. US-Turkey Workshop On Rapid Technologies, September 24 – 24, 2009

- AM has been widely used to manufacture polymer parts.⁵⁵
- The technology has begun using metal manufacturing for parts such as automotive engines, aircraft assemblies, power tools, and manufacturing tools including jigs, fixtures, and drill guides.⁵⁶

STANDARDS

With this emerging technology, there is significant demand in the literature for standards to be set for AM. The National Institute of Standards and Technology (NIST) is involved in the conversation about developing standards in AM. In late 2012, the NIST held a Roadmap Workshop on Measurement Science for Metal-Based Additive Manufacturing. At this workshop, attendees identified four technology and measurement challenges for AM:⁵⁷

1. Materials

- Limited understanding of post-processing
- Lack of monitoring for measurement of materials performance
- Lack of materials standards
- Future/Desired Capabilities:
 - AM Process Technology
 - Production Speed and Scale
 - Product Quality
 - Standards and Protocols
 - Process Measurement, Monitoring, and Control
 - Process Models
 - Knowledge and Data

2. Process and Equipment

- Industry monitor advances in material density and consistency⁵⁸
- Improve the accuracy and repeatability
- Data for feedback systems
- Future/Desired Capabilities:
 - Qualification and Certification Methods
 - Standards and Protocols
 - Reliability and Repeatability
 - Data

3. Qualification and Certification

- Create a database for public access to common alloy specifications for AM processes

4. Modeling and Simulation

- Future/Desired Capabilities:
 - Process and Materials Models
 - Model Inputs
 - Standards and Metrics to Support Modeling
 - Model Accessibility/Usability

⁵⁵ Huang, Y., Leu, M.C., Mazmunder, J., & Donmez, A. (2015). Additive Manufacturing: Current Sate, Future Potential, Gaps, Needs, and Recommendations. *Journal of Manufacturing Science and Engineering* 137, 014001-1-014001-10

⁵⁶ Energetics Inc. (2013, May). *Measurement Science Roadmap for Metal-Based Additive Manufacturing*. Prepared for the National Institute of Standards and Technology.

⁵⁷ Ibid.

⁵⁸ Price Waterhouse Cooper. (2013). 3D Printing: A Potential Game Changer for Aerospace and Defense. *Gaining Altitude*, 7. Retrieved on March 12, 2015 from www.pwc.com/us/gainingaltitude

- Moreover, improved standards must be established in AM and CAD/CAM industries. There are few tools available to track and evaluate AM equipment. This presents an opportunity for OEMs or third-parties to develop equipment monitoring systems.⁵⁹

Qualification and Certification

The manufacturing and engineering industries are a regulated industry with certifications and quality controls in order to ensure public safety. A problem exists with AM since it is a relatively new process, and consequently, it has few qualifications or certifications of standards. The creation of certification standards is essential to the wide adoption of AM.

Identical and repeatable production runs are the foundation of manufacturing, and without exact standards of replication and production, problems can arise. For example, the lack of standards has resulted in the following: incomparable material data, different process parameters based on users, limited repeatability, and limited specifications for end users to ensure production quality.^{60,61}

AM IN THE NATIONAL CONTEXT

AGENCY CONVERSATIONS

In 2014, U.S. President Barack Obama called for the creation of a Nationwide Network for Manufacturing Innovation (NNMI) to ramp-up advanced manufacturing technologies and processes.⁶² NNMI laid out 15 manufacturing centers of excellence and plans to increase this to 45 centers in 10 years.⁶³

There is a vast amount of practitioner and academic literature on AM in the national context, with many national agencies looking at the future of AM through roadmaps or technology integration. This is not surprising considering the benefits that AM can provide many of the large government procurement agencies (i.e. DoD, NASA, Department of Energy, etc.). Many agencies see the cost savings associated with AM as a good reason to invest in AM beyond its technological merit.

Federal agencies appear to be cooperating with each other to determine best uses and applications for this technology. For example, the 2009 roadmap for AM workshop, was sponsored by the National Science Foundation (NSF) and the Office of Naval Research (ONR). Beyond this, NASA and the U.S. Air Force jointly commissioned a book on the topic of 3D printing in space conducted by the National Academy of Sciences.

⁵⁹ *Additive Manufacturing in Aerospace: Strategic Implications*. (2014, August). Charlottesville, VA: Smarttech Markets Publishing.

⁶⁰ Huang, Y., Leu, M.C., Mazmunder, J., & Donmez, A. (2015). Additive Manufacturing: Current Sate, Future Potential, Gaps, Needs, and Recommendations. *Journal of Manufacturing Science and Engineering* 137, 014001-1-014001-10

⁶¹ Guo, N. & Leu, M.C. (2013). Additive manufacturing: technology, applications and research needs. *Frontiers in Mechanical Engineering*. 8(3), 215-243.

⁶² Advanced Manufacturing National Program Office. (2015). *NNMI: Snapshot*. Retrieved on March 30, 2015 from <http://manufacturing.gov/nnmi.html>

⁶³ The White House. (2013, July 30). *Fact Sheet: A Better Bargain for the Middle Class: Jobs*. Retrieved on March 30, 2015 from <https://www.whitehouse.gov/the-press-office/2013/07/30/fact-sheet-better-bargain-middle-class-jobs>

America Makes

- America Makes, formerly known as National Additive Manufacturing Innovation Institute (NAMII) was founded in 2012 and is a public-private partnership with the goal of growing U.S. strength in AM. America Makes is based in Youngstown, Ohio.⁶⁴
- America Makes seeks to accelerate the adoption of AM and 3D printing, and has described five reasons for the use of AM and 3D printing: shorter lead times, customization of products, energy reduction, product parts on demand, and enabled complexity of products.⁶⁵
- America Makes was launched with \$90 million in funding, \$30 million from the federal government and the remainder from industry sources.⁶⁶

Department of Defense

- Oak Ridge National Laboratory and Lockheed Martin are using AM to reduce the cost and scrap in the production of aerospace components. They have been using electron beam melting to produce complex aerospace parts, such as the Bleed Air Leak Detect (BALD) bracket used in the hot side of the engine on Lockheed Martin's Joint Strike Fighter.⁶⁷
- The Navy conducted a workshop in 2010 on the direct manufacturing of metallic components. The workshop participants designed a roadmap for short-term and long-term goals toward achieving AM success.⁶⁸
- PWC evaluated the adoption of 3D printing in the aerospace and defense industry. They estimated the current and future capacity of the technology:⁶⁹
 - Currently: prototypes, test units, and space craft parts are manufactured by the dozens in days
 - In 3 to 5 years: military aircraft parts, aircraft engine parts, commercial aircraft parts, and complex weapons systems will be manufactured a hundred each hour.
 - In 5 to 10+ years: munitions' components and high-volume weapons parts will be manufactured a thousand each minute.
- There are a variety of projects that AM can be used for in the aerospace and defense industry:
 - Tooling – U.S. Navy and Marine readiness carriers use AM for tooling to make one-off repairs for damaged vehicles.⁷⁰
 - Jigs, fixtures, and surrogates⁷¹
 - Production of parts of commercial and military equipment⁷²

⁶⁴ *About America Makes*. (n.d.). America Makes. Retrieved on March 31, 2015 from <https://americamakes.us/about/overview>

⁶⁵ Anderson, G. (2014, January 14) Interview with Rob Gorham, America Makes Deputy Director of Technology Development. *3dprintingstocks.com* Retrieved on March 10, 2015 from <https://3dprintingstocks.com/interview-rob-gorham-america-makes-deputy-director-technology-development/>

⁶⁶ Ford, S. (2014, March). Additive Manufacturing Technology: Potential Implications for U.S. Manufacturing Competitiveness. *Journal of International Commerce and Economics*.

⁶⁷ Dehoff, C., Duty, C., Peter, W., Yamamoto, Y., Chen, W., Blue, C., & Tallman, C. (2013, March). Case Study: Additive Manufacturing of Aerospace Brackets. *Advanced Materials & Process*.

⁶⁸ Frazier, W. E. (2010). *Direct Digital Manufacturing of Metallic Components: Vision and Roadmap*. Retrieved on March 17, 2015 from sffsymposium.engr.utexas.edu/Manuscripts/2010/2010-60-Frazier.pdf

⁶⁹ Price Waterhouse Cooper. (2013). 3D Printing: A Potential Game Changer for Aerospace and Defense. *Gaining Altitude*, 7. Retrieved on March 12, 2015 from www.pwc.com/us/gainingaltitude

⁷⁰ Schultz, M. M. (2012). *Constant Improvement: Jeff DeGrange on the State of Additive Manufacturing for Aerospace*. Eden Prairie, MN: Stratasy Inc.

⁷¹ Hiemenz, J. (2014). *Additive Manufacturing Trends in Aerospace*. Eden Prairie, MN: Stratasy

⁷² Ibid.

- Components suitable for AM: airfoils, rakes, guide vanes, impellers, and turbine blades⁷³
- Unmanned aerial systems – these are complex systems where design integration is key; this allows for production and integration at a later date.⁷⁴

Department of Energy

- The U.S. Department of Energy (DoE) Energy Efficiency and Renewable Energy Office produced a report in 2012 that looked to the future of AM. In all they found five advantages of AM:⁷⁵
 1. Lower energy intensity – saves energy because it removes production steps, enables reuse, and produces lighter products
 2. Less waste – reduces material waste
 3. Reduced time to market
 4. Innovation – eliminates traditional manufacturing design restrictions
 5. Agility – rapid response
- The DoE’s Advanced Manufacturing Office works with industry, small businesses, and stakeholders to identify and invest in additive manufacturing technologies.⁷⁶
- The DoE has initiatives to increase energy efficiency in manufacturing. AM is a key component to these goals. DoE’s Oak Ridge National Laboratory (TN) is collaborating with Cincinnati Inc., a build-to-order machine tool manufacturer, to develop large-scale polymer AM machines.⁷⁷
- DoE also created the Advanced Manufacturing Workforce Development Program with the intent of supplying more workers trained in AM.⁷⁸

NASA

- Most initiatives started by NASA have been jointly studied with the DoD. In addition, these studies are discussed in the “Aerospace & Aviation” section of this literature review.
- NASA and the U.S. Air Force contracted the National Academy of Sciences to investigate AM and its applications in space. Wright-Patterson Air Force Base, located in Dayton, Ohio, was a contributing member to the book *3D Printing in Space*.⁷⁹ Overall, this study gleaned several ideas that can be transferred to all of AM.
 - AM is very interesting for NASA since it has to transport all materials to-and-from space. Ideally, this agency would like to use AM to build a part using AM and recycle it into another part when it broke or needed fixing.⁸⁰
 - Using AM in a gravity-free environment may yield noteworthy results wherein a printer can work at one end of a part, while another printer constructs the other end.⁸¹

⁷³ Smartech. (2014, August). *Additive Manufacturing in Aerospace: Strategic Implications*. Charlottesville, VA: Smartech Markets Publishing.

⁷⁴ Schultz, M. M. (2012). *Constant Improvement: Jeff DeGrange on the State of Additive Manufacturing for Aerospace*. Eden Prairie, MN: Stratasys Inc.

⁷⁵ U.S. Department of Energy. (2012, August). *Additive Manufacturing: Pursuing the Promise*. www.manufacturing.energy.gov

⁷⁶ Ford, S. (2014, March). Additive Manufacturing Technology: Potential Implications for U.S. Manufacturing Competitiveness. *Journal of International Commerce and Economics*.

⁷⁷ Oak Ridge National Laboratory. (2014). *ORNL, Cincinnati Partner to Develop Commercial Large-Scale Additive Manufacturing System*. <http://www.ornl.gov/ornl/news/news-releases/2014/ornl-cincinnati-partner-to-develop-commercial-large-scale-additive-manufacturing-system-->

⁷⁸ U.S. Department of Energy. (2014). *Advanced Manufacturing Workforce Development (AMWD) Program*. <http://www.ornl.gov/amwd/>

⁷⁹ National Academy of Sciences. (2014). *3D Printing in Space*. Washington, D.C.: National Academies Press

⁸⁰ Ibid.

⁸¹ Ibid.

- NASA is planning to use 3D printing to manufacture rocket engine parts. Moreover, NASA reports that many of their contractors are starting to implement 3D manufacturing in their plants. This helps in overcoming the AM adoption hurdle.⁸²

National Science Foundation

The Engineering Directorate of the National Science Foundation (NSF) examined the role of NSF and other U.S. Government agencies in the development and commercialization of AM within the United States.⁸³

- In the 1980s, the NSF issued Strategic Manufacturing (STRATMAN) Initiative grants to facilitate rapid prototyping.⁸⁴ This was well received by the AM community.
- NSF has awarded almost 600 grants for AM research and other activities, amounting to more than \$200 million (2005 dollars) in funding.
- It is important to note that not all AM research found commercial success immediately and that this research can develop in several different directions. The role of the NSF as a funder of basic and strategic research is to foster research exploration.

ACADEMIA

- There is a significant amount of AM literature produced by professors and a significant amount of information on grants provided to academia, but there is little information on the role universities are playing in the AM conversation. This leads us to believe that academic researchers are involved in AM based upon their own research agenda, but little coordinated effort by universities to further AM other than research that attracts federal grant money.
- Universities that have AM centers for AM research include:⁸⁵
 - University of Texas, Austin
 - North Carolina State University
 - University of Michigan
 - California Institute of Technology
 - Penn State University
 - University of Connecticut⁸⁶
 - Carnegie Mellon University⁸⁷
 - Youngstown State University⁸⁸

⁸² Greenemeir, L. (2012, November 9). NASA Plans for 3-D Printing Rocket Engine Parts Could Boost Larger Manufacturing Trend [Video]. *Scientific American*. Retrieved on March 30, 2015 from <http://www.scientificamerican.com/article/nasa-3-d-printing-sls-rocket-engine/>

⁸³ Webber, C. L., Pena, V., Micali, M. K., Yglasias, E., Rood, S. A., Scott, J. A., & Lal, B. (2013). *The Role of the National Science Foundation in the Origin and Evolution of Additive Manufacturing in the United States*. Washington, D.C.: IDA Science and Technology. IDA Paper P-5091

⁸⁴ National Science Foundation. (n.d.). *Rapid Prototyping*. Retrieved March 31, 2015 from <https://www.nsf.gov/about/history/nsf0050/manufacturing/rapid.htm>

⁸⁵ Bourell, D. (n.d.) *Roadmaps for Additive Manufacturing – Past, Present, Future*.

⁸⁶ Poitras, C., & Reyes, A. (2013, April 5) Pratt & Whitney Additive Manufacturing Innovation Center Opens at UConn. *UConn Today*. Retrieved March 31, 2015 from <http://today.uconn.edu/blog/2013/04/pratt-whitney-additive-manufacturing-innovation-center-opens-at-uconn/>

⁸⁷ *Carnegie Mellon Receives First Round of Funding To Improve Tools for Additive Manufacturing*. (2013). Media: Featured Stories. Retrieved March 31, 2015 from http://engineering.cmu.edu/media/feature/2013/04_15_namii.html

⁸⁸ Aderholt, M. (2014, February 3). Youngstown State University Opens Center for Innovation in Additive Manufacturing. *3D Printing & 3D Printing News*. Retrieved March 31, 2015 from <http://3dprint.com/606/youngstown-state-university-opens-center-for-innovation-in-additive-manufacturing/>

- University of Louisville⁸⁹
- Case Western Reserve University⁹⁰
- There are industry and academia collaborations concerning:⁹¹
 - AM Parts
 - Non-flight critical/flight critical parts
 - AM enabled designs
 - Alternative materials
 - Meta-materials
 - Complex engine components
 - Rapid Qualification/Certification
 - AM material & process standards
 - Process models, controls, & sensors,
 - Process-microstructure-property data generation / management
 - “Digital Thread”
 - 3D/MBE/PLM and AM requirements
 - Configuration management
 - Security
 - Business and Acquisition
 - Strategies to help suppliers purchase AM technology
 - Data rights and IP
 - Cost modeling

INTERNATIONAL CONVERSATIONS AND TRENDS

The international conversation surrounding AM is multi-faceted, ranging from supply-chain processes to international development.

- AM can be seen as an aid in international development since AM technologies lower the entry barrier to manufacturing.
- AM can be beneficial in remote locations to manufacture parts and products without the need for a manufacturing plant or extensive supply-chain
- Companies and countries that are external to the current supply-chain of products can progress up the value-chain if barriers are reduced.⁹²

There are two aspects of the AM conversation in the international market: supply and demand. The supply side refers to the creation and adoption of technologies by the international market. The demand side is the desire and consumption of AM from U.S. manufacturers to the international market.

- **Supply** - AM is a technology that has been adapted worldwide; since AM was invented in the United States and U.S. holds a majority of AM patents it is sometimes regarded as the AM technology

⁸⁹ *Additive Manufacture & Rapid Prototyping* (n.d.) University of Louisville. Retrieved March 31, 2015 from <http://louisville.edu/speed/rpc/equipment-and-facilities/additive-manufacture-rapid-prototyping.html>

⁹⁰ *CWRU part of \$70 million public and private initiative to grow, improve manufacturing*. (n.d.) Case Western Reserve University, Case School of Engineering. Retrieved March 31, 2015 from <http://engineering.case.edu/additive-manufacturing>

⁹¹ McMichael, E. (2014, July 24). *Additive Manufacturing Roadmap and Key Initiatives*. Naval Air Systems Command, Presented at NAVAIR AM Industry Day

⁹² World Economic Forum. (2012). *The Future of Manufacturing: Opportunities to Drive Economic Growth*.

leader, while others suggest the opposite; allegiance seems to be dependent upon the study's country of origin.⁹³

- **Demand** - The demand for 3D printers will be driven by prototyping and direct manufacturing.
 - It is reported that worldwide demand for 3D printers is expected to rise 21% annually through 2017.⁹⁴
 - It is estimated that the 3D printer market will hit \$6 billion in 2017, up from \$2.2 billion in 2012.⁹⁵
 - A survey of 100 manufacturers by Price Waterhouse Cooper revealed that 2/3 of manufacturers are currently implementing 3D printing in some way, while 1/4 reported they plan to adopt the technology in the future.⁹⁶

EUROPE

There are disparate reports as to Europe's innovation in the AM market.

- U.S. reports show that AM is dominated by U.S. firms accounting for 70% of sales of professional-grade machines. Reports also indicate that European funding has been limited to encouraging applications rather than fostering innovation.⁹⁷
- The Direct Manufacturing Research Center at the University of Paderborn in Germany described an AM environment in Europe that is extensive and innovative, similar to the way U.S. literature characterizes the AM environment in the United States.
- European countries, especially Germany where a significant amount of manufacturing takes place, have looked to establish their own roadmaps as to what AM will look like for the future of Europe.⁹⁸

The Royal Academy of Engineering in London suggested five ways to foster AM in the future:⁹⁹

1. Increase media attention – Constant media exposure drives interest in the topic, especially among investors and inventors. They estimate that over 16,000 articles were published on 3D printing in 2012, up from 1,600 in 2011.
2. Foster UK innovation
3. Stimulate R&D through competitions – more competitions can create innovation
4. Create AM clusters – creating AM industrial clusters will foster the sharing of ideas
5. Find Entrepreneurs– attracting or highlighting bold mavericks to the industry

⁹³ Berger, R. (2013, November). *Additive Manufacturing: A Game Changer for the Manufacturing Industry?* Presentation in Munich, Germany.

⁹⁴ Freedonia Group. (2013, December). *World 3D Printing*. Cleveland, OH: Freedonia Group. Retrieved on March 10, 2015 from <http://www.freedoniagroup.com/inthenews/641440/world-3d-printing-additive-manufacturing.htm>

⁹⁵ Price Waterhouse Cooper (2014). *3D Printing and the New Shape of Industrial Manufacturing*.

⁹⁶ Ibid.

⁹⁷ Webber, C. L., Pena, V., Micali, M. K., Yglasias, E., Rood, S. A., Scott, J. A., & Lal, B. (2013). *The Role of the National Science Foundation in the Origin and Evolution of Additive Manufacturing in the United States*. Washington, D.C.: IDA Science and Technology. IDA Paper P-5091

⁹⁸ Direct Manufacturing Research Center (2011). *Thinking ahead the Future of Additive Manufacturing - Analysis of Promising Industries*. Paderborn, Germany: University of Paderborn.

⁹⁹ Royal Academy of Engineering. (2013 May). *Additive manufacturing: Opportunities and Constraints*. London: Royal Academy of Engineering.

ASIA & AUSTRALIA

- China has been investing in AM since the early 1990s, and the Chinese government pledged 1.5 billion yuan (\$245 million) to a 7-year project to advance the technology.¹⁰⁰
- Chinese businesses are eager to explore and adopt the technology.¹⁰¹
- The Asian Manufacturing Association, a Chinese-funded trade group, is creating 10 innovation institutes with an initial investment of \$3.3 million.¹⁰²
- In Singapore, the government has dedicated funding to programs to help explore AM.¹⁰³
- Australia is an interesting position regarding AM since the country is the world's largest producer of mineral sands and titanium. This country is looking to see how their role in the AM supply-chain will increase their competitive advantage.¹⁰⁴

STATE ROADMAPS AND AM CONVERSATION

In recent years, many individual states in the United States have realized that there needs to be a change in the policy agenda for manufacturing. A few years ago, the focus was how to rescue and maintain existing manufacturing; now the focus is shifting towards a different approach: how to lead the world in technologies and innovations that revolutionize manufacturing. The goal of this section is to compare and contrast the efforts undertaken by the state of Ohio with other states that have prepared strategies and roadmaps taking this new approach.

It is important to note that taking a new approach to U.S. manufacturing is relevant and important at the state level because:

1. States control public policies related to the development of innovation ecosystems;
2. States realize that while manufacturing is rapidly changing through development of new technologies, they must act quickly to make a difference for manufacturers looking to secure a competitive advantage in this industry.

AM, along with other cross-cutting technology areas such as nano-manufacturing and industrial robotics, has been considered by several states including the state of Ohio as an area for special attention. Examples of the role of states in facilitating the conditions necessary to take the lead in AM have been shown in the following ways:¹⁰⁵

- **Establishing New Programs:** Connecticut has recently launched an innovation voucher program that helps connect small and medium-sized companies to other partners and universities and encourages them to undertake R&D and innovation activities.¹⁰⁶

¹⁰⁰ Ford, S. (2014, March). Additive Manufacturing Technology: Potential Implications for U.S. Manufacturing Competitiveness. *Journal of International Commerce and Economics*.

¹⁰¹ Ibid.

¹⁰² Ibid.

¹⁰³ Ibid.

¹⁰⁴ Wohlers Associates (2011). *Additive Manufacturing: Technology Roadmap for Australia*.

¹⁰⁵ *Making our future: What states are doing to encourage growth in manufacturing through innovation, entrepreneurship, and investment*. (2013, January 1). Retrieved March 30, 2015, from <http://www.coecon.com/assets/ngamanufacturing.pdf>

¹⁰⁶ Ibid.

- **Redesigning Organizations or Creating New Ones:** Colorado Advanced Manufacturing Alliance¹⁰⁷ and the Pennsylvania Governor’s Manufacturing Advisory Council¹⁰⁸ aim at forming a consistent manufacturers’ voice about problems and policy priorities and building a strong network of relationships between manufacturers, suppliers, financiers, academic institutions, and relevant governmental agencies.
- **Passing Legislation:** California extended its community college initiative that funded manufacturing and other regional industry workforce development partnerships¹⁰⁹; and Connecticut launched a bipartisan legislative Advanced Manufacturing Caucus to identify the most important manufacturing issues for legislative action in 2013.¹¹⁰
- **Securing Funding Allocations for Manufacturing Priorities:** Massachusetts secured \$1 million for the Massachusetts Advanced Manufacturing Futures Fund¹¹¹ for initiatives focusing on five major priority areas of promoting manufacturing; workforce and education; technical assistance and innovation; the cost of doing business; and, access to capital.¹¹²
- **Taking a New Approach to Advanced Manufacturing Education and Workforce Development Programs:** A new approach to workforce development includes creating workforce intermediaries that involve industry in developing curriculum as well as in funding training administration. Two of those intermediaries are based in Washington State and both focus on aerospace (the Center of Excellence for Aerospace and Advanced Materials Manufacturing and the Aerospace Joint Apprenticeship Committee).¹¹³

STATES “BEST PRACTICE” LESSONS FOR FOSTERING ADVANCED MANUFACTURING

States have paid a specific attention to growth in advanced manufacturing in general. Advanced manufacturing goes beyond additive manufacturing and includes manufacturing that integrates technology based systems and processes for the production of goods. Yet, additive manufacturing has been considered an important subset of advanced manufacturing. The best management practice lessons presented in this section apply to advanced manufacturing in general which includes additive manufacturing.

Growth in advanced manufacturing can be achieved through innovation, entrepreneurship, and investment. Some of the best practices employed by other states include:

- Focusing on creating an environment amenable for the development of technologies, such as additive manufacturing, that drastically improve production processes or that is transformable into innovative new products rather than viewing issues from a “save manufacturing” lens;
- Realizing the opportunity to support startups and small and medium-sized manufactures to engage in advanced manufacturing in general, and additive manufacturing technologies in particular;

¹⁰⁷ *CAMA’s Program of Work*. (n.d.). Retrieved March 30, 2015, from <http://coloradomanufacturing.org/>

¹⁰⁸ *Recommendations to encourage growth in Pennsylvania’s manufacturing sector*. (2012, January 1). Retrieved March 30, 2015, from http://teampa.com/wp-content/uploads/2012/08/GMAC_FinalReportRecommendations1.pdf

¹⁰⁹ *Making our future: What states are doing to encourage growth in manufacturing through innovation, entrepreneurship, and investment*. (2013, January 1). Retrieved March 30, 2015, from <http://www.coecon.com/assets/ngamanufacturing.pdf>

¹¹⁰ *Manufacturing Caucus Created in Connecticut Legislature*. (2012, May 1). Retrieved March 30, 2015, from http://gov.cbia.com/issues_policies/article/manufacturing-caucus-created-in-legislature

¹¹¹ *Advanced Manufacturing Futures Program*. (n.d.). Retrieved March 30, 2015, from <http://www.massdevelopment.com/real-estate-development/rfps-rfq/more-info/advanced-manufacturing-futures-program/>

¹¹² <http://www.mass.gov/hed/docs/eohed/building-bridges-to-growth.pdf>

¹¹³ *Making our future: What states are doing to encourage growth in manufacturing through innovation, entrepreneurship, and investment*. (2013, January 1). Retrieved March 30, 2015, from <http://www.coecon.com/assets/ngamanufacturing.pdf>

- Recognizing that due to important developments already in process, the most immediate benefits can be gained by assembling, refining, organizing, linking or replicating, and scaling up those resources to manufacturers;
- Identifying and closing the gaps in the services, and supporting infrastructure and manufacturers' needs. The voids in supporting infrastructure can typically be due to lack of necessary services or supporting mechanisms or a mismatch between the scale and/or quality of the supporting infrastructure and needs of advanced manufacturers;
- Designating an intermediary, valued by all relevant stakeholders (particularly industry), is essential not only for the design of an effective policy framework but also for ensuring lasting support for additive manufacturing and other advanced manufacturing as a high priority in the state's policy agenda;
- Understanding the traits and mechanisms between state policy and regional action;
- Taking action to assemble immediate investments and mobilizing support for the future;
- Recognizing the first-mover advantage in securing some early achievements and building the momentum to benefit advanced manufacturers; and
- Realizing that "traditional metrics" should be updated for advanced manufacturing. More specifically, the states need to develop new metrics to capture manufacturing as a driver of innovation, productivity, and competitiveness rather than a mere job-generating source.¹¹⁴

Table 1 compares and contrasts state initiatives and their strategy development approach.

¹¹⁴ Making our future: What states are doing to encourage growth in manufacturing through innovation, entrepreneurship, and investment. (2013, January 1). Retrieved March 30, 2015, from <http://www.coecon.com/assets/ngamanufacturing.pdf>

Table 1. State Initiatives

State	Organizations, Frameworks and/or Programs	Approach to Strategy/Roadmap Development	Strategies/Areas of Focus				
			Build Institutions and networks to Promote Technology Transfer and Joint Problem Solving	Address Gaps in Access to Capital and Create a Suitable Environment for Innovation, Commercialization, and Business Expansion	Assistance to Expand into New Markets	Workforce Development Talent Attraction, and Education	Identify and Support SMEs
California	The California Economic Summit process initiated by two civic orgs: California Forward and the California Stewardship Network involving more than 1,400 Californians, who attended one of the 14 regional forums or a statewide meeting and launched 7 major “signature initiatives” in areas such as workforce development, innovation, infrastructure, access to capital, and regulatory reform	Regional, bottom-up process, involving a series of meetings of local public and private stakeholders	✓		✓	✓	✓
Colorado	Colorado Blueprint, a framework developed through regional meetings of local public and private stakeholders; The Advanced Manufacturing Steering Committee representing industry leaders from across the state; Colorado Advanced Manufacturing Alliance (CAMA), an org. guided by a board made up of the steering committee and a president and funded by private investments	Regional, bottom-up process, involving a series of meetings of local public and private stakeholders	✓	✓		✓	✓
Connecticut	NGA Policy Academy developed an action plan, with input from representatives of manufacturing companies, the state legislature, and universities, and workforce and economic development leaders in the state; Clean Energy Business Solutions created by the Department of Economic and Community Development and the Clean Energy Finance and Investment Authority to solve the problem of high energy costs; the Advanced Manufacturing Caucus to identify the most important issues for legislative action	Assembling, refining, and coordinating activities that are already in progress	✓			✓	✓

Note: SME= Small and Medium Sized Manufacturers

Table 1. State Initiatives

State	Organizations, Frameworks and/or Programs	Approach to Strategy/Roadmap Development	Strategies/Areas of Focus				
			Build Institutions and networks to Promote Technology Transfer and Joint Problem Solving	Address Gaps in Access to Capital and Create a Suitable Environment for Innovation, Commercialization, and Business Expansion	Assistance to Expand into New Markets	Workforce Development Talent Attraction, and Education	Identify and Support SMEs
Illinois	The Illinois Open Innovation Network-- a partnership between the Governor's Innovation Council, the Illinois Department of Commerce and Economic Opportunity, the Illinois Science and Technology Coalition, and Illinois' major research institutions; Manufacturing STEM Learning Exchange, a statewide public-private network to support the manufacturing talent led by the Illinois Manufacturers Association Education Foundation	Statewide public-private network coordinating resources and investments	✓	✓		✓	✓
Massachusetts	the Advanced Manufacturing Collaborative involving 5 working groups focusing on specific areas identified through the consultative process	Using statewide councils comprising large, mid-sized, and small manufacturers		✓		✓	✓
New York	Regional Economic Development Councils in each of the state's 10 regions creating their own framework (i.e. a strategic plan)	Regional, bottom-up process, involving a series of meetings of local public and private stakeholders	✓	✓		✓	✓
Pennsylvania	Governor's Manufacturing Advisory Council (GMAC): a public-private partnership between the Department of Commerce and Economic Development and manufacturing leaders and experts managed by the Team Pennsylvania Foundation	Using statewide councils comprising large, mid-sized, and small manufacturers	✓	✓	✓	✓	

Note: SME= Small and Medium Sized Manufacturers

INDUSTRY CONVERSATION

Many industries are taking the lead in additive manufacturing, such as the automotive, aerospace, biomedical, energy industries, and those involved in manufacturing consumer goods; this list is expected to grow as the technology progresses.¹¹⁵ It is estimated that adoption of 3D printing in industry will be focused in the short-term on aerospace and medical devices for their low-volume designs and small batch production.¹¹⁶ In the long-term, 3D printing can move into automotive manufacturing to aid in producing higher-end/low-volume parts, as well as after-market goods that can also benefit from after-market goods, such as white-goods, and appliances.¹¹⁷

AEROSPACE & AVIATION

It is estimated that aerospace and aviation will lead the adoption of AM.¹¹⁸ A report by Nerac quoted the 2013 Wohler Associates industry report¹¹⁹ that aerospace manufacturing use of AM will increase from \$1 million in 2012 to over \$1 billion by 2025.¹²⁰ Of all industries listed, aerospace and aviation is the ideal application for AM because part fabrication is traditionally complex and made of advanced materials in small production runs. Parts are commonly fabricated out of advanced materials such as titanium alloys, nickel super alloys, special steels, or ultrahigh temperature ceramics.¹²¹ All of these materials are difficult, costly, and time-consuming to manufacture. AM is ideal in the way that it builds parts in an additive manner, therefore manufacturers are able to use only material needed for the part.¹²² Moreover, parts involved in aerospace and aviation machines are complicated and require very technical specifications.

AM reduces the amount of material used, which is a two-fold savings for this industry: the material cost and the fuel savings resulting from lighter weight in some products.

- The consulting group Roland Berger explains further in an example¹²³: the traditional design for a seat buckle used in an airplane weighs 155g. Using AM to build an optimized seat buckle reduces the weight 55% to 70g. Using an Airbus 380 as a reference, this product then reduces the airplane's overall weight by 160 lbs. (853 seats*70g), and this equates to savings of 3.3 million liters of fuel over the plane's lifetime.
- According to Northrup Grumman, aerospace companies usually demand a 3:1 return on investment. Therefore, for every dollar spent on AM, it must receive a return of \$3 to cover implementation and maintenance costs.¹²⁴ Using this benchmark, some technology applications of AM work within these costs constraints. For example, creating low-volume parts out of composite materials for

¹¹⁵ Huang, Y., Leu, M.C., Mazmunder, J., & Donmez, A. (2015). Additive Manufacturing: Current Sate, Future Potential, Gaps, Needs, and Recommendations. *Journal of Manufacturing Science and Engineering* 137, 014001-1-014001-10

¹¹⁶ Price Waterhouse Cooper (2014). *3D Printing and the New Shape of Industrial Manufacturing*.

¹¹⁷ Ibid.

¹¹⁸ Kendrick, A. (n.d.) *3D Printing: The Next Industrial Revolution?* Tolland, CT: Nerac Inc.

¹¹⁹ **Note: Based upon the Center's research in AM, Wohler Associates reports are the most quoted reference by far. Wohler's participates in many of the road mapping projects and produces the only industry projections (for a large fee) in AM.**

¹²⁰ Kendrick, A. (n.d.) *3D Printing: The Next Industrial Revolution?* Tolland, CT: Nerac Inc.

¹²¹ Price Waterhouse Cooper (2014). *3D Printing and the New Shape of Industrial Manufacturing*.

¹²² Solid Print: Making Things with a 3D Printer Changes the Rules of Manufacturing. (2012 April 21). *The Economist* www.economist.com/node/21552892

¹²³ Berger, R. (2013, November). *Additive Manufacturing: A Game Changer for the Manufacturing Industry?* Presentation in Munich, Germany.

¹²⁴ Bourell, D. L., Leu, M. C., Rosen, D. W. (2009). *Roadmap for Additive Manufacturing Identifying the Future of Freeform Processing*. Austin, TX: The University of Texas at Austin

helicopters cost \$2,000 using a CNC machine with a 45 day lead-time but using AM, this is cut down to \$412 with a 2 day lead-time.¹²⁵

- Spare-parts industry – Researchers from the department of engineering at the Aalto University in Finland investigated the use of AM for the spare parts industry, using the aeronautics supply-chain of the F-18 Super Hornet fighter jet. The researchers investigated four scenarios of the supply-chain based upon AM machining technology and the supply-chain configuration. The authors find that AM machine price and personnel costs are the biggest obstacle to a diffused deployment of AM in the spare parts supply-chain. However, with the projected decrease in costs for the materials and machine acquisition associated with the technology overall costs will decrease as well. ¹²⁶

Some companies are exploring the use of AM in aerospace¹²⁷: (* represents companies located in Ohio)

- Boeing* - fabricating plastic interior parts out of Ultem and nylon for prototypes and test evaluation units; fabricating tools for making composite parts.¹²⁸
- Airbus – 90 separate cases where AM could be applied
- Lockheed Martin*
- Honeywell*
- Pratt & Whitney – investing \$8 million in an AM lab with the University of Connecticut.¹²⁹
- General Electric* - expecting to manufacture up to 100,000 parts with AM by 2020; also announced a \$50 million investment in a 3D printing facility in Auburn, Alabama, to make aircraft parts.¹³⁰

MEDICAL & DENTAL

AM is a natural fit for products in the medical, dental, and health sphere because most products are created and customized to the individual (i.e. hearing aids, medical implants, and dental implants).¹³¹

There are three main areas that AM plays in the medical scene:

1. Implant Fabrication
2. Bio-Additive Manufacturing (BAM)
3. Visualization Aids

Implant Fabrication

There is a sizeable amount of literature studying the use of AM to fabricate prosthetics. The community is looking to orthotics, prosthetics, and personalized implants using AM.¹³²

¹²⁵ Stratasys. (2013). *Winging It: Additive Manufacturing Reduces Tooling Cost and Lead Time to Produce Composite Aerospace Parts*.

¹²⁶ Khajavi, S. H., Partanen, J., & Holmstrom, J. (2013). Additive manufacturing in the spare parts supply chain. *Computers in Industry*. In Press. Retrieved March 10, 2015 from <http://dx.doi.org/10.1016/j.compind.2013.07.008>

¹²⁷ Ibid.

¹²⁸ Price Waterhouse Cooper. (2013). 3D Printing: A Potential Game Changer for Aerospace and Defense. *Gaining Altitude*, 7. Retrieved on March 12, 2015 from www.pwc.com/us/gainingaltitude

¹²⁹ Staff. (2013, April 4) Pratt to Provide \$8M for UConn Manufacturing Center. *Hartford Business Journal*. Retrieved on March 30, 2015 from <http://www.hartfordbusiness.com/article/20130404/NEWS01/130409900/pratt-to-provide-8m-for-uconn-manufacturing-center>

¹³⁰ Kent-Azok, D. (2014, July 15) GE Aviation plans \$50 million 3-D printing facility in Auburn to make jet engine parts. *Al.com* retrieved on March 30, 2015 from http://www.al.com/business/index.ssf/2014/07/ge_aviation_plans_50_million_a.html

¹³¹ Aliakbari, M. (2012). *Additive Manufacturing: State-of-the-Art, Capabilities, and Sample Applications with Cost Analysis*. Master's Thesis: KTH, Sweden

¹³² Centre for Process Innovation. (2014, January 30). *Additive Manufacturing for Medical Applications*. <http://www.uk-cpi.com/case-studies/additive-manufacturing-for-medical-applications/>

- Using AM by electron beam melting (EBM) has the potential to produce complicated metal implants from software models and CT scan data. The researchers include dental implants, face implants, and orthopedic implants.¹³³
- Additional success creating knee and hip implants using AM EBM.¹³⁴

Bio-Additive Manufacturing (BAM)

Many reports cite the potential use of AM in the medical setting. This is referred to as Bio-Additive Manufacturing (BAM). BAM is the “bio-fabrication using cells, biologics or biomaterials as building blocks to fabricate biological and bio-application oriented substances, devices, and therapeutic products through a broad range of engineering, physical, chemical and/or biological processes.”¹³⁵ Bio-fabrication can encompass a wide range of applications from tissue science and engineering to organ printing.

- The U.S. Food and Drug Administration, the agency in charge of medical device approval, held a workshop in October 2014 on AM of medical devices.¹³⁶ This workshop was geared to address questions surrounding the technical considerations of AM of medical devices.
- Researchers understand the importance of working with the FDA on these products since the FDA plays a large regulatory role in this area. One article advised that it is important to peruse development of tissue constructs or matrices in a way that is acceptable to the FDA to translate it to clinical outcomes since this technology will most likely be classified as a “combination product.”¹³⁷
- Many of these technologies are not widely available outside of academia or research hospitals. For example, Organovo created the first bioprinter, the NovoGen MMX.¹³⁸ Organovo’s first biological product will be liver tissue for drug testing since liver problems are the most common reason for a drug to be pulled from the market.¹³⁹
- Researchers at Wake Forest University’s Medical Center are currently adapting commercially available ink jet printers to bioprint organs and tissues.¹⁴⁰
- Each day bioprinting becomes more sophisticated. Researchers are learning how to work replicate tissues and organs. Instead of piping cells into Petri dishes by hand, research at Wake Forest led to the creation of artificial scaffolds that provide a temporary matrix for cells to hold onto until they

¹³³ Murr, L.E., Gaytan, S.M., Medina, F., Lopez, H., Martinez, E., Machado, B.I., Hernandez, D. H., Martinez, L., Lopez, M.I., Wicker, R.B., & Bracke, J. (2010). Next-generation biomedical implants using additive manufacturing of complex, cellular and functional mesh arrays. *Philosophical Transactions of the Royal Society A*, 368 (1917), 1999-2032.

¹³⁴ Ibid.

¹³⁵ Bourell, D. L., Leu, M. C., Rosen, D. W. (2009). *Roadmap for Additive Manufacturing Identifying the Future of Freeform Processing*. Austin, TX: The University of Texas at Austin

¹³⁶ U.S. Food and Drug Administration. (2014, December 2). *Public Workshop - Additive Manufacturing of Medical Devices: An Interactive Discussion on the Technical Considerations of 3D Printing, October 8-9, 2014*. Retrieved March 19, 2015, from FDA: <http://www.fda.gov/MedicalDevices/NewsEvents/WorkshopsConferences/ucm397324.htm#materials>

¹³⁷ Ibid.

¹³⁸ Organovo. (2015). *Organovo: NovoGen MMX Bioprinter*. Retrieved March 19, 2015 from Invetech: <http://www.invetech.com.au/portfolio/life-sciences/3d-bioprinter-world-first-print-human-tissue/>

¹³⁹ Leckhard, S. (2013, August 6). How 3-D Printing Body Parts Will Revolutionize Medicine. *Popular Science*. Retrieved March 19, 2015, from Popular Science: <http://www.popsi.com/science/article/2013-07/how-3-d-printing-body-parts-will-revolutionize-medicine>

¹⁴⁰ Wake Forest School of Medicine. (2015, February 8). Using Ink-Jet Technology to Print Organs and Tissue. Retrieved March 19, 2015 from Wake Forest: <http://www.wakehealth.edu/Research/WFIRM/Our-Story/Inside-the-Lab/Bioprinting.htm>

can stand on their own. From there, researchers found that using AM can create scaffolds more precisely, which is helpful for more complex tissue structures.^{141, 142}

Visualization Aids

- Medical modeling and visualization is used in hospitals around the world to create prototypes for surgical planning, prosthetics, and related applications. At times, surgeons and patients need a 3D object to grasp the problem at hand.¹⁴³
- This technique is so popular that recently a U.S. television show “Grey’s Anatomy” – a hospital drama – featured the hospital staff using a 3D printer to print a tumor to visualize the problem.¹⁴⁴

MANUFACTURING

- There are many uses for AM in traditional manufacturing. AM has started to penetrate the tooling market, especially when it is a complicated part or casting. There are two ways that AM can be used in tooling: indirect – using AM in pattern making, or direct – producing the insert or dyes themselves.¹⁴⁵
- Companies have used AM to manufacture parts and components for racing vehicles that use ultra-lightweight materials and have complex structures like aerospace.¹⁴⁶

¹⁴¹ Leckhard, S. (2013, August 6). How 3-D Printing Body Parts Will Revolutionize Medicine. *Popular Science*. Retrieved March 19, 2015, from Popular Science: <http://www.popsci.com/science/article/2013-07/how-3-d-printing-body-parts-will-revolutionize-medicine>

¹⁴² Melchels, F.P.W., Domingo, M. A. N., Klein, T.J., Mald, J., Bartolo, P.J., & Hutmacher, D.W., Additive manufacturing of tissues and organs. *Progress in Polymer Science*. 37 (8), 1079-1104.

¹⁴³ Rengier, F., Mehndiratta, A., von Tengg-Kobligk, H., Zechmann, C.M., Unterhinninghofen, R., Kauczor, H.U., & Giesel, F.L. (2010). 3D Printing based on Imaging Data: Review of Medical Applications. *International Journal of Computer Assisted Radiology and Surgery*. 5 (4), 335-341.

¹⁴⁴ Edwards, T.E., (2015, February 15). Grey’s Anatomy” Prominently Features Medical 3D Printing Technology. *3D Printer & 3D Printing News*. <http://3dprint.com/43211/greys-anatomy-3d-print-heart/>

¹⁴⁵ Aliakbari, M. (2012). *Additive Manufacturing: State-of-the-Art, Capabilities, and Sample Applications with Cost Analysis*. Master’s Thesis: KTH, Sweden

¹⁴⁶ Huang, Y., Leu, M.C., Mazmunder, J., & Donmez, A. (2015). Additive Manufacturing: Current Sate, Future Potential, Gaps, Needs, and Recommendations. *Journal of Manufacturing Science and Engineering* 137, 014001-1-014001-10

TAKEAWAYS & POLICY IMPLICATIONS

- ✓ There is a sizeable need for **regulation of AM**.
 - Individual industries are regulating AM within the construct of the organization’s mandate (i.e., FDA for medical devices, FAA for airplanes, etc.), but there are no overarching standards for AM.
 - The ATSM has done the heavy lifting to bring about international definitions of AM, but there needs to be a national push either through industry associations or the federal government to bridge the gaps in standards. It is important, however, for these standards to remain flexible because of the evolution and innovation happening within this technology.
 - Standards need to be established in:
 - Metrics: measurement methods and performance metrics
 - Process: create standards in how to construct a product and ways to facilitate repeatability
 - Organization and coordination is fragmented among industries in AM; there is a need, therefore, to engage all stakeholders (government, academia, and industry) to discuss industry collaboration.¹⁴⁷

- ✓ There seems to be significant energy in both industry and government to increase the adoption of AM. However, there is **little evidence to suggest that industry, academia, and government are working together** in significant public-private partnerships to adopt and enhance AM. Siloed approaches include:
 - Significant federal inter-agency cooperation to use and adopt AM for government uses (i.e., defense, space exploration, and aviation).
 - Energy in academia to push the boundaries of AM and its application (i.e., use for medical devices and manufacturing).
 - Industry has widely adopted AM for cost-cutting measures such as rapid prototyping and small-batch manufacturing.

- ✓ In order for widespread adoption of AM across the field of manufacturing there needs to be **tangible evidence as to cost-saving measures**. There is a significant amount of academic literature, involving calculus and complicated modeling methods, to evaluate the cost savings of AM, but this esoteric literature cannot and will not appeal to the average business.
 1. Currently there are industry best practices of how AM can benefit the bottom line and improve product quality in aerospace and aviation. However, scenarios need to be built for all manufacturing industries.
 2. The main costs’ drivers in AM are machine investment, raw material costs, and pre- and post-production actions.¹⁴⁸ As AM technology becomes mainstream, machinery and material costs will decrease while technology and output will increase; this will reduce the overall costs to AM adoption.

¹⁴⁷ Science Technology Policy Institute (2012). *Additive Manufacturing: Status and Opportunities*. Washington, DC

¹⁴⁸ Lindemann, C., Jahnke, U., Moi, M., & Koch, R. (2012) *Analyzing product lifecycle costs for a better understanding of cost drivers in additive manufacturing*. Paper presented at the 23rd Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference, Austin, TX, 6th–8th August, 2012. Retrieved March 30, 2015 from <http://sffsymposium.engr.utexas.edu/2012TOC>

- ✓ There is a **need to understand the global AM market**. Throughout this literature review, there have been confounding reports as to who is the market leader: the United States or Europe. It is important to understand the market and its global players for several reasons:
1. There is significant amount of concern in the AM community regarding intellectual property (IP) rights. If the U.S. is a major player in AM, it would be beneficial since the U.S. is a sovereign power that will establish IP laws. Therefore, if a majority of the companies are within the United States, there will be only one set of laws to deal with. However, if the United States is not the dominant player, then U.S. companies must deal with international organizations or different countries' laws in order to protect each IP. Understanding the global landscape can protect U.S. profits.
 2. Aerospace and aviation is one of the largest segments of the AM market. The U.S. military plays a significant role in this industry and is concerned about 3D printing companies being housed in other countries.¹⁴⁹ Moreover, there could be concerns about dual-use technology issues. Understanding the global landscape can protect U.S. security.

¹⁴⁹ Appleton, R.W. (2014). *Additive Manufacturing Overview For The United States Marine Corps*. RWApleton & Company