Environmental and Health Impacts of Additive Manufacturing

An NSF Workshop Report:
Environmental Implications of Additive Manufacturing

October 14-15, 2014

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July 2015

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Executive Summary

On Oct. 14-15, 2014, the Science and Technology Innovation Program at the Woodrow Wilson International Center for Scholars and the Center for Manufacturing Innovation at the University of Florida sponsored a workshop at the National Science Foundation (NSF) to explore the environmental and human health implications of the growing field of additive manufacturing. This workshop was designed to build on a previous NSF-funded workshop held in July 2013, "Frontiers of Additive Manufacturing Research and Education." The October 2014 workshop explored five areas of additive manufacturing: lifecycle impacts, occupational health, energy use, waste and cross-cutting/policy issues.

After the workshop, an online survey was sent to the presenters and participants to help rank the identified research areas. This report summarizes the research questions discussed at the workshop, combining additional input from the discussion leaders and the results of the online survey. The participants identified the following areas where further research is needed to better understand the potential environmental implications of additive manufacturing.

Lifecycle Assessment Issues: Research is needed into the supply chain footprint of additive manufacturing and the methodologies needed to compare entire pathways, from material extraction to finished product. There was also interest in a standardized assessment of process energy consumption for additive manufacturing. This research should utilize plausible scenarios looking towards the future of additive manufacturing methods.

Occupational Health Issues: There is a need for better risk assessment and management research related to additive manufacturing, including the toxicology of emissions, exposure control approaches and exposure assessment. This work could include the development of "Safer by Design" principles, tools and approaches for additive processes.

Energy Use Issues: Research is needed into new materials, quantifying the energy impacts of the products of additive manufacturing and developing standardized methodologies to compare energy use of additive with conventional manufacturing processes. This work might include consideration of lightweight materials, batteries, insulation or energy production technologies.

Waste Issues: There is a need for research into management at the end of life of products made with additive manufacturing, in addition to work on industrial production waste and whether novel shapes, products and parts made possible by additive manufacturing pose unique challenges for waste management.

Cross-cutting and Policy Issues: A variety of research policy research needs were identified, particularly further research into the regulatory implications of bio-printing. Other areas identified include risks unique to additive manufacturing in "desktop" settings, liability for different types of users in different settings (schools, job shops, etc.), the use of lifecycle analysis by different constituent groups and the public perception of various uses of additive manufacturing.

I. INTRODUCTION

1.1 Background

Additive manufacturing (AM) embraces a wide range of technologies, from desktop 3D printers costing a few hundred dollars to industrial machines costing millions of dollars. They all use an "additive" process, where successive layers of material are selectively placed to build up an object, as opposed to traditional "subtractive" machining techniques, which rely on removal of material by methods such as cutting, grinding or drilling. AM has been used by industry since the 1980s to build prototypes of parts or products, helping to speed up product innovation.

What is new and attracting a great deal of attention is that high-end industrial printers are increasingly being used to create final products and inexpensive printers are bringing 3D printing to the desktop and potentially tens of thousands of new users. The technology is proving especially valuable for producing highly complex shapes, one-of-a-kind objects and customized variations on a basic design. AM can be cost-effective for short manufacturing runs and makes it possible to produce parts when and where needed. Capabilities like these, combined with continuing progress in printing technology, are driving rapid growth in the AM market. A summary of the history of AM can be found in the report for "Frontiers of Additive Manufacturing Research and Education," a National Science Foundation (NSF) workshop held in July 2013 [1].

Proponents of AM technology often assert that it has major environmental benefits compared to conventional manufacturing. Common claims are that AM produces less material waste, is more energy efficient and reduces energy use and associated emissions in transportation by manufacturing locally or on site. Some argue AM can be used deliberately to foster sustainability. Parts can be printed only when needed, avoiding excess or unsold production and the energy and economic costs of storage. Easy production of replacement parts can extend product lifetimes and associated lifecycle impacts. Products customized to meet personal needs or preferences could be less likely to be thrown out.

As yet, however, little research has been done to test these assertions and carefully assess the environmental impacts of AM. The Science and Technology Innovation Program at the Woodrow Wilson International Center for Scholars began looking at these environmental issues for "3D Printing: A Boon or a Bane?," an article published as the cover story in the November/December issue of the *Environmental Forum* [2]. The article highlights the paucity of research on environmental and human health impacts.

In the article, Robert Olson of the Institute for Alternative Futures discusses the history of the technology and summarized existing AM research on material waste, energy efficiency, toxicity concerns, recycling and the danger of "overprinting" as printing becomes increasingly easy and inexpensive. Olson concludes the evidence to date suggests that many of the environmental claims for AM are exaggerated and that sweeping generalizations about the potential environmental and human health impacts of AM are inappropriate because there are so many different AM processes and so many materials used in printing, ranging from thermoplastics, epoxy resins, nylon, ceramics, titanium, aluminum and steel alloys to chocolate and frosting.

The article includes a proposal for a Green Design Framework for 3D printing roughly based on programs like the Environmental Protection Agency's (EPA) Design for Environment program. It makes the case that, because decisions with the greatest environmental impacts are generally made during the earlier design stages, what is needed most now is a widely accepted set of principles to influence those early-stage decisions.

1.2 Objective

To go deeper than the *Environmental Forum* article, the Science and Technology Innovation Program worked with the University of Florida and NSF to design a workshop on "Environmental Implications of Additive Manufacturing." The purpose of the workshop was to bring together experts in AM technology and researchers with backgrounds in industrial ecology, energy and materials, mass balance assessments, lifecycle analysis and environmental risk assessment to identify knowledge gaps and uncertainties that can inform an agenda for future research into the environmental and health impacts of AM.

The workshop's major outcome is the research agenda presented here outlining environmental research needs related to AM. Another outcome is to expand the research community focused on these issues and create the potential for ongoing collaborations. We hope these efforts will lead to improvements in the assessment of AM and support the evolution of AM technologies with lower environmental and energy impacts.

1.3 Workshop overview

The day-and-a-half NSF workshop was held Oct. 14-15, 2014 at the NSF headquarters in Arlington, Virginia. The event's first day had two goals: (1) to provide general education about the potential environmental implications of AM to a diverse audience and (2) to begin the process of identifying research gaps and uncertainties that could be addressed by further research. Day one included overview sessions on AM processes, materials, vendors and markets and futures uses, followed by sessions on environmental implications, lifecycle issues, human health issues and energy-use issues. The day concluded with a summary discussion to organize questions for day two, as well an opportunity to discuss funding needs with NSF officials.

Day two of the workshop began with a summary of the questions raised at the end of day one, followed by five sessions discussing lifecycle analysis, occupational health, energy use, waste and policy questions. Discussion on the second day focused on input from 30 invited attendees and around 60 observers from the public, which allowed environmental researchers and stakeholders to discuss key research gaps and needs in selected areas.

The workshop had 96 officially registered participants including organizers, presenters, discussion leaders and stakeholders from academia, government and industry. Appendix A includes the full list of organizers, discussion leaders and invited speakers. The workshop was funded by two divisions of NSF’s Engineering Directorate, the Civil, Mechanical and Manufacturing Innovation Division's Manufacturing Machines and Equipment Program and the Chemical, Bioengineering, Environmental and Transport Systems Division's Environmental Sustainability Program.

1.4 Research agenda

This report summarizes the main research needs and data gaps identified by the speakers and participants on day two of the workshop, creating a preliminary agenda for research on the environmental and health implications of AM. Each chapter in the next section corresponds with a discussion session on day two of the workshop.

In addition to a summary of the workshop discussions, each chapter includes the results of an online survey conducted after the workshop, which drew input from 31 participants who voted on the importance of various research needs discussed at the workshop and identified by the discussion leaders. Respondents were asked to rate each research need on a scale from 1 (not very important) to 5 (very important). Respondents could also suggest their own research needs via free-form response boxes. Charts throughout the report show the importance assigned to each research need. The full text of the survey can be viewed online [3].

Though occupational health and policy-related research fall outside of NSF’s mandate, participants felt that an improved understanding of impacts of process and product changes related to AM could inform occupational health and environmental policies at agencies such as the EPA, National Institute for Occupational Safety & Health and National Institutes of Health (with respect to bio-printing).

II. RESEARCH AREAS

2.1 Lifecycle Assessment Issues
(Discussion lead: Dr. Martin Baumers, University of Nottingham)

2.1.1 Current State of the Art (Lifecycle Assessment)

Lifecycle assessment (LCA) contributes to the understanding of a durable good's performance and impact over the course of its life, from raw material generation to disposal at the end of life (EoL). Among other things, LCA helps understand the item's cumulative environmental footprint and informs decisions about materials, design, processes and supply chains. LCA requires measurements at every stage of an item’s life and analysis of LCA often informs and leads to trade-offs in the production process.

The potential of AM to produce complex objects at little or no additional cost raises interesting questions for LCA, particularly whether energy consumption increases with additional complexity and what implications that might have for part performance during its use phase. The potential of AM to lower costs and be more energy efficient than conventional processes could raise interesting policy and regulatory questions, as well. Research is needed to improve methodology and develop scenarios to produce accurate LCA to compare various manufacturing methods and the supply chains in which they are embedded.

2.1.2 Lifecycle Assessment Research Needs

Participants in the workshop strongly indicated the need for new methodologies and scenarios to better understand AM’s supply chain implications, as well as better methods for comparative assessments of energy use and EoL considerations.

In the discussion session on LCA issues faced in AM, six distinct areas for research were identified:

1. Research into methodologies to establish the supply chain footprint of AM pathways
2. Scenarios for environmental impact of AM-enabled innovation of the supply chain
3. Standardized assessment of process energy consumption for AM and conventional routes
4. Research into the impact of making AM technology production ready
5. Research on how LCA can be more effective through the availability of more data
6. Assessment of whether EoL considerations change after the wide diffusion of AM technologies

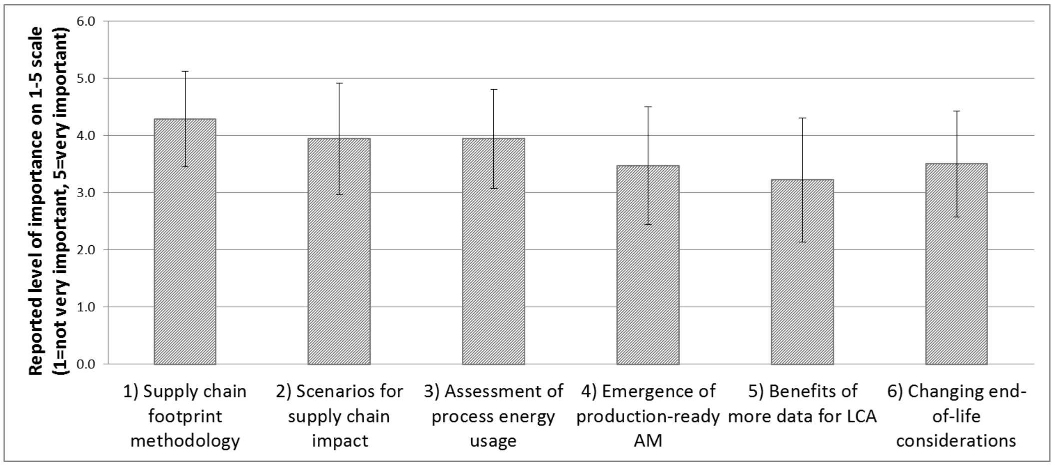

Figure 1. Level of importance of LCA research areas

(Error bars represent +/- one standard deviation for applicable figures.)

Figure 1 reports the mean values for the levels of importance of these research areas, as reported by participants in the online survey. The data indicate that four areas of research are perceived as especially important: research into methodologies to establish the supply chain footprint of AM; scenarios for environmental impact of AM-enabled supply chains; standardized assessment of process energy consumption for AM; and assessment of changing EoL considerations with increased use of AM.

2.1.3 Recommendations for Lifecycle Assessment Research

Participants in the discussion session focused on these four priority areas where further LCA research is needed. These key areas are discussed in the bolded sections below, in addition to a brief discussion of additional LCA-related research areas and two comments submitted via the online survey.

Supply Chain Footprint Methodology: Participants indicated that the most important research area relating to LCA is the establishment of methodologies that are capable of capturing the supply chain footprint of AM in order to compare the impact of alternative manufacturing pathways (both AM and conventional). In total, 84 percent of survey respondents indicated this research area to be moderately to very important.

The supply chain footprint covers the “cradle-to-gate” aspects of manufacturing. Analyses of this type aim to generate a detailed understanding of the environmental impacts occurring as energy and materials are translated into finished products. The supply chains of AM-based manufacturing are marked by the digital integration (virtualization) and consolidation of manufacturing and assembly processes into individual AM process steps. This is contrasted by conventional mass-manufacturing supply chains, which are often characterized by a multitude of process steps, potentially performed at different locations around the globe.

A number of additional aspects are identified for consideration when building methodologies to capture the environmental impact of AM supply chains. First, the use of AM in true manufacturing settings may require integration with complementary, potentially conventional, manufacturing techniques, opposed to prototyping applications. An example for such requirements is the need to improve surface quality or tolerances to an acceptable level. Second, proposing AM for routine manufacturing settings suggests a significant increase in manufacturing volume. Therefore, the methodologies designed to capture the environmental footprint of AM supply chains must be able to reflect the scalability of such digital fabrication processes (or lack thereof). Additionally, it is suggested to incorporate the mass flows of raw materials and products into AM supply chain models.

The participants suggested that the research requirements for the development of new methodologies for comparing the supply chain impact of AM with alternative processes could be implemented through specific pathway analyses for AM applications.

Scenarios for Supply Chain Impact: A further research area perceived as highly important in the context of LCA issues is the development of scenarios projecting the environmental impact of AM adoption in manufacturing supply chains. According to the survey, 69 percent of respondents placed this research area in the top two categories. A number of aspects to consider in such scenarios were identified in the discussion session, including the co-distribution of energy and raw material supply together with AM systems and the impact of consumer-operated AM systems. It is noted that these scenarios should consider all three dimensions encompassed by the concept of sustainability, environmental impact, societal factors and commercial/economic benefits. Undertaking a scenario-building effort is likely to lead to the identification of additional research requirements.

Assessment of Process Energy Use: Workshop participants supported more research to develop standardized and systematic methodologies for the assessment of process energy consumption on AM systems and conventional processes. It is suggested that a consistent and reliable methodology to capture energy inputs can be supported by a benchmarking effort based on the thermodynamic minimum of energy needed to convert the required raw materials into the product configuration. Moreover, it is commented that this research need can be addressed by forming a research network aimed at standardized process energy assessment.

Change of End-of-Life Considerations: The final aspect deemed highly important by respondents is the need for research establishing whether EoL considerations must be adapted for the wide-scale adoption of AM technology. Particular points raised in the workshop are the effects on product obsolescence, the possibility to re-manufacture products created via AM pathways and EoL considerations for products customized on the basis of personal data (such as patient-specific medical products). An additional identified research requirement is to establish a precise understanding of the waste streams resulting from decommissioned AM products.

Below these four priority areas, two additional research areas were reported as less important by the respondents to the survey: the emergence of production-ready AM equipment and the assessment of benefits that may arise from an increased ability to collect lifecycle data.

In the online survey question, research towards making AM technology production-ready was phrased as “mass production of AM equipment,” which differs from the scope of the corresponding research area as discussed in the workshop. The original suggestion was to assess the impact of technologically evolving AM systems for greater compatibility with mass production settings (“productionizing”). It is noted that scaling AM technology, in particular by increasing machine throughput, is associated with improvements of platform energy efficiency. Moreover, raw material requirements and logistics should be considered as determinants of environmental performance as the install base/diffusion rate of AM increases.

Research into the benefits of increased availability of lifecycle data was judged to be the least important area by the respondents. The perceived low level of importance may be a manifestation of one of the arguments made during the session: There appears to be a requirement to communicate to the manufacturing community that cheap sensing and data processing are enabling technologies for data-rich LCA and that such approaches are “no longer hard to do.” It was felt by the participants that measurement of the use-phase benefits of advanced designs is an important aspect for a manufacturing technology capitalizing on an ability to create such complex and efficient product features.

Two additional materials-related comments were submitted in the free-form section of the survey. First, a general suggestion was made to view research into raw materials for additive processes in the light of the environmental impact during the lifecycle of products. Relevant aspects in this context could be to establish a degree of transparency in the energy embedded during raw material generation or any pre-determined material waste streams resulting in AM, for example, due to material refresh rates or material expended for sacrificial support structures. The second suggestion was to extend LCA analyses to encompass the environmental effects of using AM to create multi-material structures or hybrid composites.

2.2 Occupational Health Issues

(Discussion lead: Dr. Andrew Maynard, University of Michigan)

2.2.1 Current State of the Art (Occupational Health)

AM processes have the potential to reduce the hazards that are endemic to many conventional manufacturing processes – they may in principle be self-contained, use less material and produce less waste. Yet they also present the possibility of emergent risks. Understanding and addressing both the potential risks and benefits of AM to users across the board is critical to the fully realizing advantages these AM technologies present.

While many forms of AM now emerging present a step-change from more conventional manufacturing techniques, the health and safety risks they present are often not that dissimilar to those found in any industrial setting. For example, working with hazardous materials, operating processes that can cause physical injury and managing harmful emissions are common to many forms of manufacturing. However, AM technologies are also giving rise to emerging risks. In addition to the use of unusual feedstock and novel processes, there is the increasing risk of common hazards being encountered in uncommon settings. AM is making the production of one-off and small-run items accessible to new communities and, as a result, the places, people and situations associated with these technologies are diverging from the typical profiles seen with more conventional manufacturing processes. Sophisticated AM processes are, for instance, being used in startups, small prototyping shops, maker spaces, basements, garages and even classrooms. In these cases, while many of the risks to health and safety may not be that dissimilar to those encountered in other manufacturing processes, the institutional knowledge and ability to identify and handle them is.

This emerging combination of conventional hazards in unconventional contexts, and unconventional hazards within risk-naïve communities, is creating a unique set of challenges and uncertainties to ensuring the economic and societal benefits of AM through ensuring safe and responsible use. To better understand potential alternatives and scenarios, a list of AM materials, feedstocks, organization types, processes and post-processing can be found in Table 1 in Appendix C, along with a set of four scenarios of AM use across these alternatives.

2.2.2 Occupational Health Research Needs

Following in-depth discussions of the challenges of ensuring health and safety while taking advantage of AM, five areas of research were identified:

1. Research and development into “Safer by Design” approaches to AM
2. Exposure assessment research
3. Research into developing safer community practices
4. Risk assessment and management research
5. Research into innovation in education

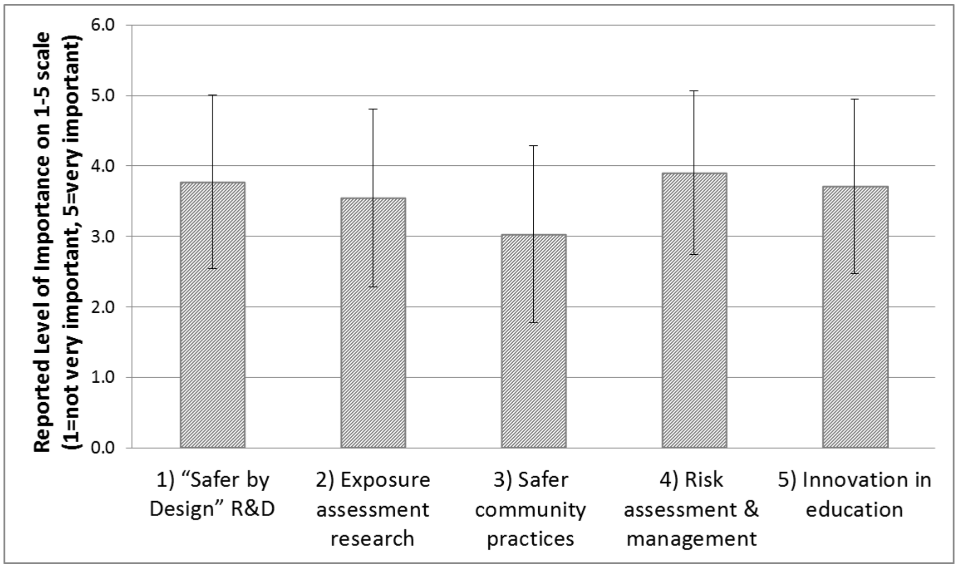

Figure 2. Level of importance of occupational health research areas

(Error bars represent +/- one standard deviation for applicable figures.)

Figure 2 reports the mean values for the levels of importance for these research areas, as reported by respondents to the online survey. Workshop participants identified three top research priorities: risk assessment and management; creating tools and guidelines for ensuring “safer by design” processes; and assessing exposure to potentially harmful substances.

2.2.3 Recommendations for Occupational Health Research

Participants in the discussion session focused on three priority areas where further occupational health research is needed. These key areas are discussed in the bolded sections below, in addition to a brief discussion of additional health-related research areas and an overall concluding note.

Risk Assessment and Management: Some 85 percent of workshop participants polled considered research into risk assessment and management around AM to be of moderate to high importance, with 41 percent considering it to be “very important.” There was specific concern over the potential risks of gaseous and particulate emissions, especially where these may take the form of nanoparticles. While there are few reasons why well-designed processes could not manage such emissions to the point of them not being a health risk, it was felt that in some application areas there is not a strong culture of managing such emissions: 3D printer use in educational settings was one extreme example where susceptible individuals could be inadvertently exposed to harmful airborne emissions.

There was also concern expressed over the toxicity and hazardous nature of feedstock materials – in particular where fine powders and metal powders are used. In some cases, particularly metal powders, explosion hazards may exist that will not necessarily be properly identified and managed. Cutting across these concerns was the issue of poorly understood chronic health impacts and the possibility that seemingly innocuous exposures could lead to long-term health impairment.

One concern specific to AM is the challenge of assessing and managing risks associated with prototyping and producing bespoke items. In these cases, because each job is likely to be unique, the need for new approaches to ensuring adequate risk assessment and management were raised. From the discussion, it was clear that there is an urgently needed body of research into innovative, cross-disciplinary and multi-stakeholder approaches to assessing and managing the risks associated with manufacturing in a way that will enable the technology to meet its potential.

Safer-by-Design approaches: According to the survey, 85 percent of respondents considered research and development of "safer-by-design" approaches to AM to be of moderate to high importance. Participants recognized that there is the potential to develop safer-by-design methodologies, standards and cultures from an early stage within AM, before unsafe practices have become locked in. However, research is needed into what this means within different contexts – from large-scale manufacturing to startups, prototyping and even maker communities. Progress here will depend on interdisciplinary collaboration to ensure that manufacturing guidelines draw on the latest understanding of risk management, governance and use of design principles and approaches. It will also depend on approaches that extend across the life stages and value chain of AM processes and products.

Exposure assessment: According to the survey, 78 percent of workshop participants polled considered research into assessing exposure to hazardous substances from AM to be of moderate to high importance. Complementing the need for research into risk assessment and management, an urgent need was identified for exposure information on potentially impacted populations, from workers to local communities. This would need to be mapped out across communities, from startups and maker communities to large-scale businesses. Developing integrated exposure assessments and profiles around AM technologies and practices will be a critical step toward understanding and managing potential risks and implementing innovative risk management approaches, such as control banding and safer-by-design approaches. Importantly, it will not be possible to make significant progress on managing risks and developing safer-by-design approaches without baseline data on exposures. These should include full materials and exposure characterization using the latest techniques available.

Below these priority areas, the issue of safer community practices was raised, as distinct from safer-by-design approaches to ensuring health and safety. This goes beyond safer-by-design concepts and risk management by considering emerging communities of users that lack a culture and history of safe manufacturing, such as maker communities, small startups, schools and hobbyists. There is increasing recognition that the lines are being blurred between educational, hobby and commercial use with AM, although there is a dearth of information on the nature of exposures and risks within exposed populations and the types of good practice guidelines and mechanisms that may be effective in reducing risk/increasing safety. Educational settings were of special concern, where large-scale, inadvertent exposure to emissions (including fine particulates) could occur within a young and vulnerable population, as well as leading to long-term exposures with staff. At the same time, it was recognized that AM – 3D printing, in particular – is a powerful learning and engagement tool that could be used effectively in increasing interest in science, technology, engineering and mathematics subjects and careers. This potential makes developing safe use guidelines all the more important within an educational setting.

Overall, there was a general understanding that some of the most pressing potential health risks connected with AM were associated with use of unfamiliar technologies by inexperienced personnel – in other words, unexpected risks that are novel and need addressing because they are not intuitive or expected. There was some concern that, as AM becomes more widespread, innovation in materials used for feedstock may lead to highly unusual exposures, including inhalation exposures to hybrid, composite, nanoscale and other advanced materials. More importantly, from the discussion there emerged a need for responsible approaches to innovation and practice in AM to ensure the technology is developed and used as safely as possible and to ensure sustainable development through managing perceived, as well as actual, risks to health and safety.

2.3 Energy Use Issues

(Discussion lead: Joe Cresko, Department of Energy)

2.3.1 Current State of the Art (Energy Issues)

Because of the unique nature of AM technology, many key questions surround its energy impacts. One major challenge to understanding the energy efficiency of AM is the fact that machines vary widely in how much energy they use and that energy use is dependent on a variety of variables, including materials, load and use patterns and geographic distribution.

For example, studies have shown that some 3D printers use up to 80 percent more energy than comparable conventional processes. Industrial AM fusion methods using metal powders and high-energy beams can consume much more electricity per unit than conventional manufacturing methods, though there may be overall gains by allowing complex parts to be produced in a single step, avoiding the energy impacts of multiple part production and assembly. In some cases, AM methods have been shown to be more efficient with low production runs, but conventional methods become more efficient with higher production.

2.3.2 Energy Use Research Needs

To begin to answer these questions, workshop participants agreed further research is needed to better understand the energy impacts of the new materials and processes used in AM.

In the discussion session on energy issues in AM, four key research areas were identified:

1. Research into standardizing methodology to characterize manufacturing processes
2. Research into the opportunities/impacts of new materials' functionality
3. Research into the high-energy impacts from AM/distributed manufacturing technologies
4. Best practices for communicating outcomes and engaging with the community

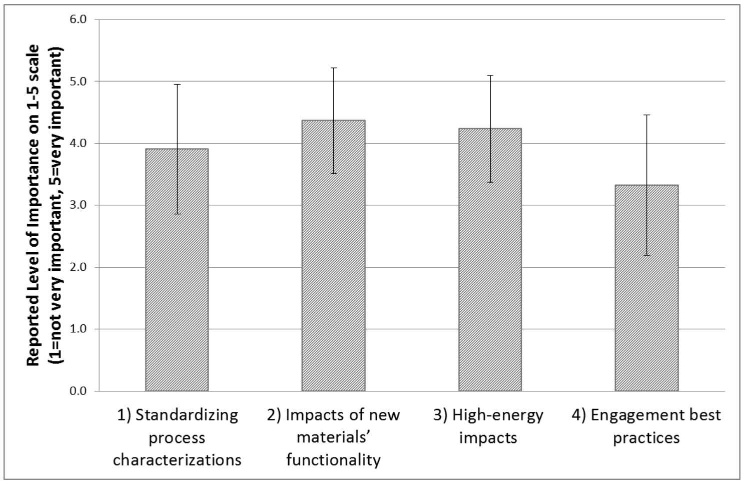

Figure 3. Level of importance of energy research areas

(Error bars represent +/- one standard deviation for applicable figures.)

Figure 3 shows the mean values for the levels of importance of these research areas as reported by workshop participants in the online survey. The data indicate that three areas of research are perceived as especially important: research into new materials; research into process energy impacts; and research into standardized methodology.

2.3.3 Recommendations for Energy Use Research

Participants in the discussion session focused on three priority areas where further energy research is needed. These key areas are discussed in the bolded sections below, in addition to a brief note about additional energy-related research.

Research into new materials: Of the workshop participants, 78 percent felt it was moderately to very important to conduct research into the energy-related opportunities and impacts presented by the functionality of new materials, including polymers, metals, bio-materials, ceramics and multi-materials. In the survey, 53 percent of respondents identified this area as "very" important.

There are concerns about the refined materials used in AM methods, as these materials are often in powder or rod form and use more energy in their production. But AM could employ new materials with less embedded energy or that help increase overall production efficiency by eliminating subsequent assembly processes. In the future, the use of bio-materials in AM might allow for recyclability at scale, though there could be drawbacks to these new bio-materials that would need to be explored.

Novel materials could also be used to create new structures that contribute to energy storage, so the energy-intensive AM processes themselves may be balanced out with products that are more energy efficient and used in a variety of mass-marketed consumer products.

Research into process energy impacts: Some 75 percent of workshop participants indicated that research into the high-energy impacts for AM and distributed manufacturing technologies were of moderate to high importance. This work could focus on the secondary impacts of using AM to reduce energy used in other sectors, for instance by "lightweighting" automobiles or airplanes, or in the production of energy technologies, such as batteries or insulation.

During the discussion session, there was a threshold question raised about whether the processes used were critical to the end-product needs and whether unnecessary processes were being used to reach the same end point as traditional methods. The Department of Energy (DOE) has started to look at the lifecycle and embedded energy associated with AM processes. To this end, DOE's Oak Ridge National Laboratory is conducting an LCA designed to better understand the total process implications of AM.

As discussed at the meeting, creating lighter aluminum alloy and steel structures via AM methods would be ideal. Lightweighting large frames, like those used in automobiles, can result in cars with a higher fuel efficiency that produce lower emissions. But the production rates for items used in the mass production of items like cars would most likely not be fast enough to justify the use of these methods.

There was also interest expressed in finding ways to create distributed manufacturing centers integrated within the energy system, allowing the manufacturing work to be tied in with the overall energy network. With this sort of system, manufacturing work could also be timed to make for more efficient use of energy during different times of the day.

When considering energy efficiency, it might also be important to look at the production side, including equipment and buildings, considering the constrained and efficient nature of energy use in making materials. It was also suggested that work could be done to understand whether the heating of residential and commercial buildings could be coupled with the AM process to help reduce waste and increase efficiency.

Also, when considering metals and the fusion processes, which have been shown to use more energy than traditional processes, there is the potential to increase efficiency with better choice of metal stocks and post-production processes.

Standardized methodology: According to the survey, 62 percent of the workshop participants felt it was moderately to very important to conduct research into the standardization of methodologies used to characterize AM processes, particularly when compared to conventional manufacturing, looking at different steps in the manufacturing process and measuring embedded energy.

This work could be based on European test methods already in use or getting better access to the expensive machines that are able to measure the amount of energy used and lost in the production process.

Finally, some 41 percent of workshop participants indicated support for research into best practices for publishing and communicating outcomes and engaging with standard-setting organizations, the educational community and existing government assets like America Makes and the DOE's national laboratories.

2.4 Waste Issues
(Discussion lead: Reid Lifset, Yale University)

2.4.1 Current State of the Art (Waste)

The unique characteristics of AM processes mean there is potentially less waste produced when compared with traditional manufacturing processes. But the distributed nature of AM raises questions about the amount of waste that could be generated in non-industrial settings.

The research needs related to AM and waste are largely ones of scoping. Little systematic information exists about the nature and quantity of the wastes generated in the use of AM. This is especially true for the use of AM in non-industrial settings. For all of the issues described below, quantitative information is needed regarding current and emerging practices related to AM. Without that information, it is difficult to investigate more specific questions. This information should include the type and quantity of materials used in AM, the settings in which they are used, and the waste generation rates for production and EoL products.

2.4.2 Waste Research Needs

In the discussion session on waste issues, four distinct areas for research were identified:

1. Research into how EoL products should be managed
2. Research into production waste in both industrial and non-industrial settings
3. Research into the drivers of/barriers to product lifetime extension enabled by AM
4. Research into whether novel shapes, products and parts made possible by AM pose unique challenges for waste management

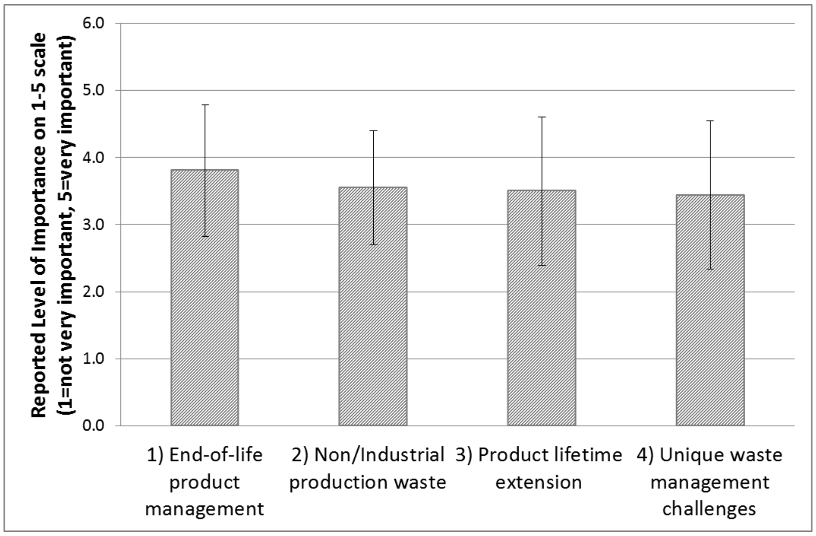

Figure 4. Level of importance of waste research areas

(Error bars represent +/- one standard deviation for applicable figures.)

Figure 4 reports the mean value for the levels of importance assigned to each of these areas by workshop participants in the online survey. The data indicate that three research areas are perceived as particularly important: research into management of EoL products; research into industrial production waste; and unique waste management challenges.

2.4.3 Recommendations for Waste Research

Participants in the discussion session focused on three priority areas where further waste research is needed. These key areas are discussed in the bolded sections below, in addition to another related research area.

Managing End-of-Life Products: Some 56 percent of workshop participants considered research into how EoL products are managed to be of moderate to high importance. AM raises potentially unique issues with respect to the management of EoL products. This includes both products wholly produced through AM and products containing parts produced using AM processes (called “AM products” here for convenience).

AM holds out the possibility of the use of novel materials or those that have not been previously widely used. New materials and wastes may require new or different means of management. For example, a product that was previously recyclable may become less so and thereby require changes in sorting by the waste generator and a different destination in the waste management system.

The challenges posed by AM products produced at the EoL depend in part on whether the products are disposed of by consumers or in an industrial setting because the latter have management systems for the control and segregation of wastes because of hazardous waste regulation and because of conventional business incentives to minimize the cost of waste management. In contrast, households, non-industrial businesses and institutions are less accustomed to more elaborate procedures for waste handling.

Novel materials may pose challenges to recycling systems because of the need to identify and process products using new materials. Similarly, novel materials may present engineering or environmental threats to composting, incineration or landfilling.

Multi-material AM products pose similar challenges of handling by waste generators, changes in recyclability, identification of relevant products for separate management and new forms of waste processing. Multi-material AM products can pose particularly notable challenges for recycling because many recycling operations operate on narrow profit margins, making the use of additional capital equipment for sorting and processing uneconomical.

The challenges of novel materials and multi-material AM products might be addressed through design for EoL where the AM products are designed to avoid toxic constituents or facilitate recycling. Widespread adoption of design for EoL may be hindered by the diversity of consumer and small business settings where AM may be used and by continuing innovation in AM products that makes investment in design for EoL uneconomic.

Production waste issues: Some 56 percent of workshop participants indicated that research into production waste issues in industrial and non-industrial settings, including recyclability and hazards, was of moderate to high importance.

The challenges arising from waste from the production of AM products largely mirror those from EoL wastes, i.e., management of novel or previously less-widely occurring wastes. Like EoL wastes, issues related to production wastes in industrial settings can build on existing procedures for waste handling both with respect to hazardous materials and recyclable materials. AM can lead to less waste on a per-product basis due to the nature of the additive production process. Whether this is significant in aggregate depends on the wastes generated in producing AM feedstock and in the particular AM processes used, some of which are not waste free. To the extent that AM products are produced in smaller quantities than conventionally manufactured products, with commensurately less waste generated, the quantities of scrap be less economic to recycle.

In non-industrial settings, a key challenge may be the use of materials that are potentially toxic or difficult to manage in a setting where there is little familiarity with the relevant necessary procedures.

Unique waste management challenges: Some 54 percent of workshop participants indicated that research into whether the novel shapes, products and parts made possible by AM pose unique waste management challenges. These challenges may be processing challenges posed by the equipment used in recycling and disposal. Another issue raised at the workshop was the unique waste issues posed by 3D bio-printing for use in medical applications. To the extent bio-printing becomes a technology used by consumers and small businesses, bio-printing may lead to the need to extend medical waste management practices or infrastructure to new domains.

Some 50 percent of workshop participants indicated that research into the possibility of product lifetime extension by AM was of moderate to high importance. This represents one of the more intriguing opportunities posed by AM with respect to waste management: the possibility of extending product life spans by increasing repairability of products and the availability of spare parts. AM might be used to produce custom parts for repair of products (i.e., specific to the aspect of the product needing repair) and could also be used to produce spare parts on demand without the need for large production runs of those parts. In a similar vein, remanufacturing products at the commercial and/or industrial scale may similarly benefit from custom production of parts. An important issue to resolve in this respect is the intellectual property rights associated with spare parts. This includes both the availability of information that facilitates production of spare parts and repair (manuals, schematics) and whether aftermarket producers of spare parts and consumers/hobbyists may not possess the relevant rights to produce those parts.

2.5 Cross-cutting & Policy Issues (Discussion lead: Mark Greenwood, Greenwood Environmental Associates)

2.5.1 Current State of the Art (Cross-cutting & Policy)

AM technology raises a variety of potential policy issues that cut across topical areas. The distributed nature of AM poses potential emergent risks and, while industrial users of the technology would work within existing regulatory and governance frameworks, an increase in novel workplaces for AM, such as job shops and maker spaces, could raise new issues regarding policy guidance.

3D bio-printing, which employs AM techniques to print and space cellular material and may support important medical advancements, could raise its own regulatory and disposal questions. Other aspects of AM where further research is needed include public perception, liability and other legal issues, trade agreements, material traceability agreements and security issues.

2.5.2 Cross-cutting and Policy Research Needs

Generally, participants felt that the potential “distributed” nature of the technology could pose novel environmental and exposure risks and test the existing policy frameworks, though the use of the technology by established companies in the manufacturing space would largely be addressed by existing regulatory frameworks.

Following this wide-ranging discussion session, three policy areas were identified and polled in the online survey:

1. Research into policy issues related to distributed manufacturing generally and how bio-printing adds further complexity and sensitivity

2. Research into LCA methodologies and their value to different constituents
3. Research into the public perceptions of the "retail" uses of AM, including gauging trust in existing regulatory frameworks

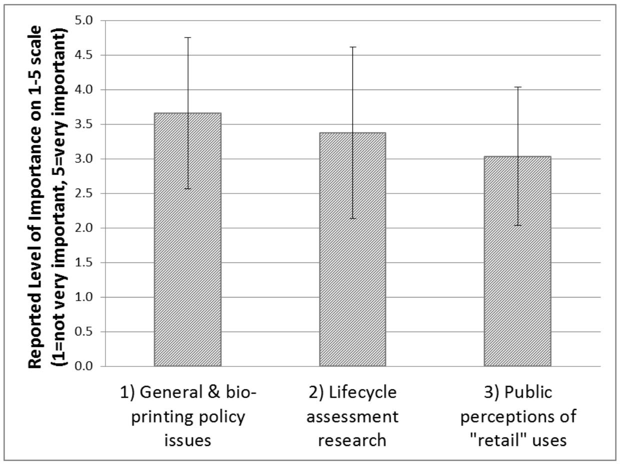

Figure 5. Level of importance of policy research areas

(Error bars represent +/- one standard deviation for applicable figures.)

Figure 5 reports the mean values for the levels of importance of these research areas, as reported by participants in the online survey. The data indicate that research into general and bio-printing policy was perceived as particularly important.

2.5.3 Recommendations for Cross-cutting and Policy Research

Participants in the discussion session focused on three priority policy areas where further research is needed. General and bio-printing policy issues are discussed in this section, followed by a brief discussion of additional policy-related research areas and a list of other research needs that were raised during the policy discussion and in the online survey.

During the workshop there was considerable discussion concerning how to best approach the impact and risks from the "desktop" side of AM, which would take place outside of regulated industrial settings. Part of the concern was on how to assess the growth potential and development paths of the various distributed models, such as job shops, maker spaces and home users. There might also be research gaps surrounding what information should be provided to schools and other "desktop" users, as well as a need to provide better information about legal liability to these types of users. All of these issues are less of a concern for AM being used with the existing manufacturing sector because systems are already in place for the industrial side and can more easily be adapted.

In the online poll, some 56 percent of respondents felt it was "important" or "very important" to conduct further research into the issues related to distributed manufacturing in general and, in particular, how bio-printing could create another layer of complexity to risk assessment and policy.

Participants expressed less urgency concerning other potential research areas. Slightly less than 50 percent of survey respondents thought it was “important” or “very important” to conduct further research in how LCA could be used or what value assessments provide to different audiences in the policymaking community. Participants pointed out that LCAs are used differently when produced for internal or industry use compared to an assessment applied to a distributed production system. Other research gaps could include how the distributed profile of AM relates to other “distributed” technologies, such as “open source” software and “open electronics.”

Less than 30 percent of respondents felt it “important” or “very important” to conduct research into the public perception of the “retail” uses of AM, work that could include gauging the trust in the existing regulatory frameworks. But this work could be useful in understanding public perceptions of risks and benefits.

Because of the cross-cutting nature of the policy session, a number or research gaps were discussed that did not fit neatly into the identified research areas. The research gaps include:

- Social science research into how the public actually responds to increased use of AM and its potential benefits and risks
- Additional research into end-user interactions with the technology, including the use of 3D printers in schools and the regulatory and legal issues that flow from this
- Copyright issues that come from increased use of AM
- Material traceability impacts as the technology becomes increasingly distributed
- Questions surrounding legal liability, particularly with regard to spare parts and the use of the technology in public places like schools
- Trade agreements and security issues, including what can be printed in different geographic areas in accordance with the law and how is that controlled

In the free-form survey response, one respondent encouraged the development and dissemination of a sustainability framework for AM, similar to EPA’s Design for Environment label. Olson discusses this concept in his November/December 2013 *Environmental Forum* piece on the environmental implications of AM, where he encourages those involved with AM ensure the sustainability of the production and energy/resource efficiency of 3D printers, use renewable and biodegradable feedstocks, design machines and feedstocks for safe use, develop take-back and recycling programs and provide easy-to-understand information on safe use and risk reduction [4].

III. CONCLUSIONS

The “Environmental Implications of Additive Manufacturing” workshop sought to provide a diverse audience with general education about the potential environmental implications of AM and to start to identify knowledge and data gaps that could be addressed by further research. This report begins to outline myriad research topics that will help better understand how distributed AM systems at the desktop, job shop and industrial levels will impact the environment and human health.

In the wide-ranging discussion sessions and follow-up survey, participants indicated there is a great appetite for additional work in these areas, from better-informed LCAs to a better understanding of what risks could be posed by AM in non-traditional use settings. The discussion sessions also illustrated that the field of AM is rapidly advancing and changing. New technologies are constantly coming online, as evidenced by new high-speed AM methods like “continuous liquid interface production technology,” or CLIP. At the same time, because of the decentralized nature of AM, *where* AM is used to make things could change as fast as *how* AM is used to make things. For instance, home hobbyist use of AM may give way to a greater use of local job shops, or a brand new model may emerge to fill existing or emerging production niches. This means that any research program will have to be adaptive, forward looking and interdisciplinary.

This workshop brought together researchers working in manufacturing and engineering with those looking at environmental and health risks, many of these experts meeting for the first time. But more work is needed and, in some cases, is already beginning. *The Journal of Industrial Ecology* (http://bit.ly/JIE-AM_CfP), for example, has secured initial funding to produce a special issue looking at this very topic, meaning this peer-reviewed journal will be a place to collect articles focused on the latest research. The workshop website (http://www.nsfamenv.wilsoncenter.org) has been expanded to include the presentations from the workshop, as well as information about additional funding opportunities in the space. This site could be updated and used as an interim resource as this work continues.

As stated in the introduction, there is hope the workshop, this report and subsequent efforts will lead to improvements in the assessment of AM and support the evolution of AM technologies with lower environmental and energy impacts. If you would like to contribute to this work or have any comments or concerns, please contact the report authors (david.rejeski@wilsoncenter.org, yongh@ufl.edu) or the report editor (aaron.lovell@wilsoncenter.org).

Acknowledgments

The report was compiled from workshop notes and the online survey and includes input from most discussion section leaders: Dr. Andrew Maynard of the University of Michigan (Occupational health), Dr. Martin Baumers of the University of Nottingham (Lifecycle analysis) and Dr. Reid Lifset of Yale University (Waste). Dr. David Rosen of the Georgia Institute of Technology provided four scenarios of current AM practice and a table of different factors (Table 1), which appears in Appendix C. Robert Olson of the Institute for Alternative Futures provided input for the background section. Joyce Koo of the Wilson Center assisted with the production of the graphs in the report. Elizabeth Tyson and Robert McNamara of the Wilson Center took notes and assisted with workshop logistics. We wish to thank all of them for their assistance.

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Appendix A

Organizers, Discussion Leaders and Invited Speakers

Organizers

David Rejeski	Woodrow Wilson International Center for Scholars
Yong Huang	University of Florida

Report Editor

Aaron Lovell	Woodrow Wilson International Center for Scholars

Discussion Leaders

Martin Baumers	University of Nottingham (Lifecycle Issues)
Andrew Maynard	University of Michigan (Occupational Health Issues)
Joe Cresko	Department of Energy (Energy Use Issues)
Reid Lifset	Yale University (Waste Issues)
Mark Greenwood	Green Wood Environmental Counsel (Cross-cutting & Policy Issues)

Invited Presenters

David Rosen	Georgia Institute of Technology (Overview of Processes for Additive Manufacturing)
David Bourell	University of Texas (Overview of Materials Used in Additive Manufacturing)
Gideon Levy	Additively.com/TTA (Additive Manufacturing Meets Sustainable Environment Needs)
Ming Leu	Missouri University of Science and Technology (Future Opportunities for AM Technologies and Applications)
Robert Olson	Institute for Alternative Futures (Additive Manufacturing: Environmental Boon or Bane?)
Martin Baumers	University of Nottingham (Impact of Product Shape Complexity on Process Energy Consumption in Additive Manufacturing)
Brent Stephens	Illinois Institute of Technology (Ultrafine Particle Emissions from Desktop 3D Printers)
Tim Gutowski	Massachusetts Institute of Technology (An Energy Research Agenda for Additive Manufacturing)

Appendix B

NSF Sponsoring Programs

ENG Directorate

Division of Civil, Mechanical and Manufacturing Innovation (CMMI)
Manufacturing Machines and Equipment (MME) Program: Zhijian Pei

Division of Chemical, Bioengineering, Environmental and Transport Systems (CBET)
Environmental Sustainability Program: Bruce Hamilton

Appendix C

Scenarios for Addressing Potential AM Issues (Adapted from Dr. David Rosen, Georgia Institute of Technology)

The following table that outlines many of the alternatives that currently exist in AM and could form the basis for further discussion of potential environmental and human health implications, as well as many of the research needs discussed in this report.

Table 1. Various Alternatives Currently Existing in AM

Material	Feedstock Form	Process	Organization Type	Post-Processing	Customer Location
Polymer	Powder	Material Extrusion	Industry	Blow off powder	Local
Metal	Filament	Material Jetting	Maker Space	Sand/file/finish	Within State
Ceramic	Liquid	Powder Bed Fusion	Home/Consumer	Paint	US
	Sheet	Vat Photopolymerization		Solvents	World-wide
		Binder Jetting		Furnace	
		Directed Energy Deposition		Machine	
		Sheet Lamination			

The four scenarios outlined below are illustrative of how and where AM is currently used and could raise key questions about the environmental and human health effects of various AM practices.

Scenario 1: Production of Metal Powder Bed Fusion Parts

A company has 40 metal powder bed fusion (PBF) machines that are producing metal (assume Titanium-6Al-4V) parts for production purposes 24 hours a day, seven days a week. Each fabricated part replaces 15 conventionally manufactured parts that had to be assembled and brazed into a complex sub-assembly. Each PBF part is half the weight of the previous 15-part design. In addition to simple part clean-up, several key surfaces on the PBF parts have to be machined. Each PBF part is approximately 200 mm x 150 mm x 100 mm. Parts are delivered to an assembly line on-site.

Scenario 2: Production of Polymer Powder Bed Fusion Parts

A company has 15 polymer PBF machines that are producing parts in nylon for production purposes 24 hours a day, seven days a week. Each fabricated part is custom designed for a specific customer. The product replaces several conventionally manufactured alternatives that varied widely in their materials and manufacturing processes (assume textile straps, plastic plates, buckles, etc.). Experiments have demonstrated significantly superior use outcomes with the polymer PBF parts. Simple part clean-up is performed (blowing away powder). Each PBF part is approximately 250mm x 100 mm x 100 mm. Individual parts are shipped to customers across the United States.

Scenario 3: Community Center Maker Space

A community center has 20 consumer-grade 3D printers that use material extrusion (e.g., stems). Customers run the machines, which are available for individuals building parts, for experts building parts on-demand for customers and for teachers to use in classroom instruction. Each printer can be assumed to be operating 50 percent of the time the community center is open (9 am to 9 pm). Some machines build supports using the part plastic, while others use a separate material (assume polyvinyl alcohol) that dissolves in water.

Scenario 4: Metal Part Repair using Directed Energy Deposition

A local shop has two directed energy deposition machines that are used primarily to repair metal parts. Materials that can be deposited include tool steel, titanium alloys, cobalt-chrome and Inconel alloys. The shop serves a wide range of customers and parts to be repaired are in a wide range of conditions (e.g., clean, dirty, oily, greasy). Every part requires finish machining, which is done on site. Most customers are within 200 miles of the shop; many are within 50 miles.

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