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Prototyping the Environmental Impacts of 3D Printing: Claims and Realities of Additive Manufacturing

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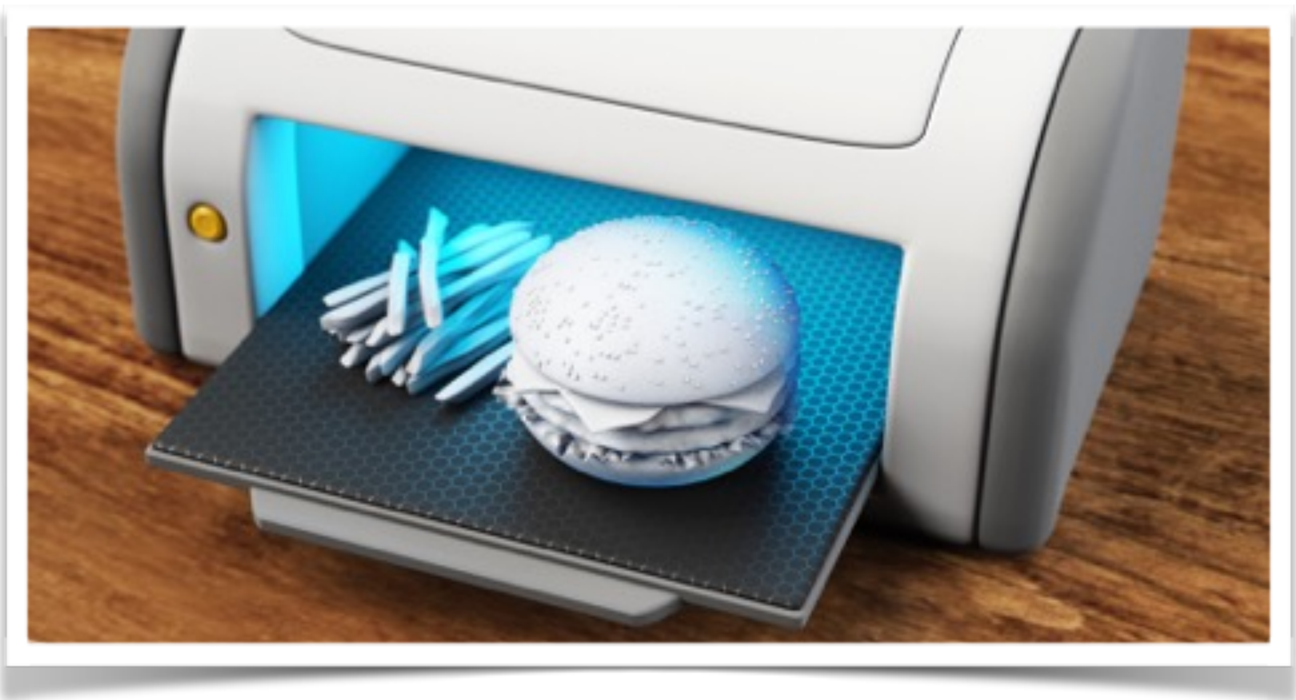
Prototyping the Environmental Impacts of 3D Printing:

Claims and Realities of Additive Manufacturing



Source: Maciej Frolow

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Abstract

3D printing has the potential to become a disruptive technology by cutting down on the environmental and time costs associated with traditional manufacturing processes. For example, supply chains and product storage could essentially be eliminated if product design became entirely digital. Although 3D printing is potentially highly beneficial for the environment, awareness of 3D printing's impact on the environment is essential for healthy development and should be addressed before the technology is used on an industrial scale. The purpose of this research is to discuss the environmental aspects of additive manufacturing. By objectively examining 3D printing sustainability claims and case studies, an understanding of 3D printings' environmental effect on society will be made. The research takes an interdisciplinary approach, analyzing economic risks, carbon and ecological footprints, and how the field is currently regulated, in addition to how it may be regulated in the future. By using historical and market data, a clear understanding of the 3D printing market can be established. I will examine the various methods used to formulate the industry's environmental impacts. By examining case studies, 3D printing's environmental impact will be evaluated. Focusing on what current laws and regulations apply to 3D printing and what laws could be applied in the future, the research aims to understand how environmental costs are and should be minimized.

Introduction. The Risks of a 3D Printed Future

The rise of environmentalism began when the world watched the United States drop atomic bombs on the Japanese cities of Hiroshima and Nagasaki. At that moment, the world began to fully recognize how human consumption and new technologies have the capacity to negatively affect human civilization on a planetary scale. Similarly, when humans began to take responsibility for the damage they had done to the natural climate, new technologies were offered up as universal remedies for climate-change. However, time and time again, the United States has shown a troubling addiction to fossil fuels that causes those same new technologies to be ignored. In turn, advancement and conservational causes are hindered while oil, coal, gasoline, natural gas and other traditional fuel sources are ingrained into society as necessary evils. What experts say will be the "next big thing" is currently *additive manufacturing*, a process where three-dimensional products are created by typically printing successive layers of material; this process is also called 3D Printing. Headlines around the world regularly claim this technology will restore marine life, fight climate change, end world hunger, and provide affordable housing for the impoverished. Research presented in this paper supports these claims too, however 3D printing is ultimately not a cure-all that will solve the climate crisis in the United States. History has shown that there are serious dangers when our society dismisses or accepts a technology, especially when research and policy recommendations are disregarded.

One of the most prominent examples of when America has irresponsibly rejected and accepted a technology is inarguably nuclear power. Nuclear power brought promising environmental solutions in the 1940's, but fears about radioactivity, meltdowns, nuclear weapons and the unknown caused people to second guess its capability to supply energy safely. Although life cycle assessments show nuclear power plants emit negligible amounts of greenhouse gases in comparison to fossil fuels, the world currently produces far more of its electricity from fossil fuels than nuclear energy[1]. Nuclear power plants accounted for only 10.8% of the world's electricity production in 2012, while fossil fuels still dominated global primary energy consumption. In 2013, the United States generated only 19% of its electricity from nuclear power. In that same year, more than 40% of American electricity came from coal. But Americans still reject nuclear power so vehemently that the debate has become incredibly controversial, and even environmentalists are torn on its merits. The reason for this is because of how quick America was to embrace this radical new field of science without first adequately researching the dangers. Validly, there are also those who know of nuclear power's potential, but also believe governments cannot take the risks seriously enough for nuclear power to be worthwhile.

Fears of radiation and nuclear materials originate from when Marie Curie discovered radium as an element, exposing how radium destroys tumor-forming cells faster than healthy cells.[2] This pioneering research sadly fostered a profound misuse and acceptance of radium in the following years. In 1925, William Bailey created a popular elixir called "A Cure for the Living Dead" containing "radium-226 and radium-228." Radium-226 and radium-228 are poisonous elements whose dangers were easily ignored when Bailey claimed it cured "150 diseases from high blood pressure to dyspepsia."[3] People began drinking radium water to the point where it

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[1] McIntyre, Jamie, Brent Berg, Harvey Seto, and Shane Borchardt. "Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources." *World Nuclear Association Report* (2011): 6.

[2] Mahaffey, James. *Atomic Accidents: A History of Nuclear Meltdowns and Disasters*. New York: Pegasus, 2015: 567

[3] Mahaffey, James. 617.

was wildly sought after; there were even radioactive cocktails.[4] When socialite Eben Byers consumed significant amounts of Bailey's elixir, his bones disintegrated, resulting in him losing most of his jaw. Byers died a gruesome death – holes forming in his skull - at age 52. His death heightened the public's awareness and fears of consuming radium. In 1990, the Wall Street Journal unearthed and re-examined a newspaper article written after his death titled, "The Radium Water Worked Fine Until His Jaw Came Off."[5]

Another radium horror story involves female workers who painted watch dials with radioactive paint at the United States Radium Factory in Orange, New Jersey. Around 1917, the factory told their workers that the radioactive paint was harmless, and the workers were encouraged to lick their paintbrushes while working. Licking the paintbrushes tapered them to a point, making it easier to paint the dials with precision. This resulted in hundreds of women dying from radiation sickness as they were ingesting lethal amounts of radium.[6] These workers became infamously known as the "Radium Girls." Attitudes towards the dangers of radiation grew more serious after nuclear weapons formed mushroom shaped clouds in the sky that destroyed cities and instantly killed approximately 105,000 people.[7] The world watched, horrified, as the radiation continued to slowly kill even more Japanese citizens for decades. The American public's appetite for nuclear power was slowly fading, and after the meltdowns that occurred at Chernobyl, 3 Mile Island and Fukushima Daiichi, opinions inevitably worsened.

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[4] Mahaffey, James. 718.

[5] Winslow, Ron. "The Radium Water Worked Fine Until His Jaw Fell Off." *Wall Street Journal.* New York: 1990.

[6] Mahaffey, James. 758.

[7] Stoll, Steven. *U.S. Environmentalism since 1945: A Brief History with Documents.* Boston: Bedford/St. Martin's, 2007.1.

People at first couldn't get enough of radium water and its curative properties, until their bones began falling apart. Nuclear power was exciting and potentially utopian research, until core meltdowns and radioactive waste created miles and miles of uninhabitable space. Nuclear power is a much cleaner technology and better for the environment when used safely and appropriately, yet fossil fuels remain a dominant force. Even accounting for every nuclear meltdown in history, only one person per nuclear power plant dies through directly relatable causes a year on average worldwide, while four thousand people die from direct causes from each coal powered plants in the same period of time. [8] These statistics do not even take into account deaths from external environmental impacts. The fact that Americans rely more heavily on fossil fuels than nuclear power shows American willingness to reject a technology without fully taking into account the facts. Like a true addict, the dangers of fossil fuels are denied, hidden, and protected with money used to pay off the media and government regulators. Playing up the risks of nuclear power makes clinging on to fossil fuels that much easier.

Similar to the radium water, 3D printers are currently offering medical advancements previously unheard of. For example, bio-printing, a process of manufacturing new organs using living tissue as ink, is a concept that is attempting to eliminate the antiquated practice of placing patients on long waitlists for organ transplants. That same fear of new technology, with so much unknown, easily makes newcomers and naysayers nervous about drinking the 3D printed "elixir." Ironically, if the medical advancements that 3D printing offers were available in Byer's day, he could have printed himself a new jaw just as an eighty year old woman did in 2013, when

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[8] "Deaths per TWH by Energy Source." *Next Big Future.* 13 Mar. 2011. Web.

a customized 3D titanium jaw implant was printed for her.[9] Bone implants, Invisalign® braces, and artificial limbs are just a few ways 3D manufacturing is already advancing medical fields. However, 3D printing is a new technology and significant research is needed to take into account the risks and benefits it poses to the environment. Diving into the unknown rightly causes fear, but how do we keep those fears in check so that we do not disrupt the technology's growth, development and potential? How do we prevent the horrors of our past naivety with new technologies from occurring within our homes if 3D printers become readily available to consumers?

Evaluating 3D printing's effect on the environment is a task that involves examining the subject through interdisciplinary fields. Understanding 3D printing's effect on society is impossible without understanding the current market of 3D printing, its carbon and ecological footprint, its economic risks, and how the field is currently regulated, in addition to how it may be regulated in the future. 3D printing is potentially highly beneficial for the manufacturing industry, however awareness of 3D printing's policy practices, how they are formed, and how they impact the environment is essential in a product's development and must be addressed before the technology can be used on an industrial scale. By using historical and market data, Chapter 1 will establish a clear understanding of the 3D printing industry, explaining the trends and issues that the industry faces. Chapter 2 outlines the various methods used in this research to analyze the industry's environmental impacts. Evaluating the sustainability claims made by the industry and using methods developed in the previous chapters, Chapter 3 assesses 3D printing's

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[9] Kaelin, Brooke. "First 3D Printed Titanium Jaw Implant Successful." *3D Printer World.* 16 Aug. 2013. Web. 28 Mar. 2015.

environmental impact. Chapter 4 focuses on what current laws and regulations apply to 3D printing, examining negative and positive externalities, and what laws could be applied in the future to minimize environmental costs. The conclusion will be left semi-open-ended, urging others to research more on this astonishing topic. By reflecting on previous chapters, the conclusion builds on the previously stated policy recommendations and creates predictions on how the industry might challenge and completely change the world, as we know it in 2015.

Chapter 1. The Makers Behind the Movement

"I think 3D printing is almost a marketing term. 3D printing is manufacturing-it can be a dirty and messy process. We use chemicals, and depending on what I'm doing in here sometimes I wear a gas mask."
-John T. Lee (3D Printing Specialist at *ABC Imaging*)

3D printing refers to any of the additive manufacturing methods that create a three dimensional product.[10] Additive manufacturing (AM) techniques are different than traditional manufacturing techniques that use blocks of raw material and remove the excess (subtractive manufacturing), or techniques that shape liquid or raw material into a hollowed out mold (molding manufacturing). AM is an umbrella term referring to any technique that creates objects from 3D model data, by fusing layers of material together from a base. Electronic design files are created using computer-aided design (CAD), that modifies, analyzes and optimizes designs or through the use of 3D scanners. The software then "slices models into cross-sectional layers" and sends the file to an additive manufacturing printer.[11] New methods of additive manufacturing are

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[10] Lipson, Hod, and Melba Kurman. *Fabricated: The New World of 3D Printing.* Indianapolis: John Wiley & Sons, 2013: 66.

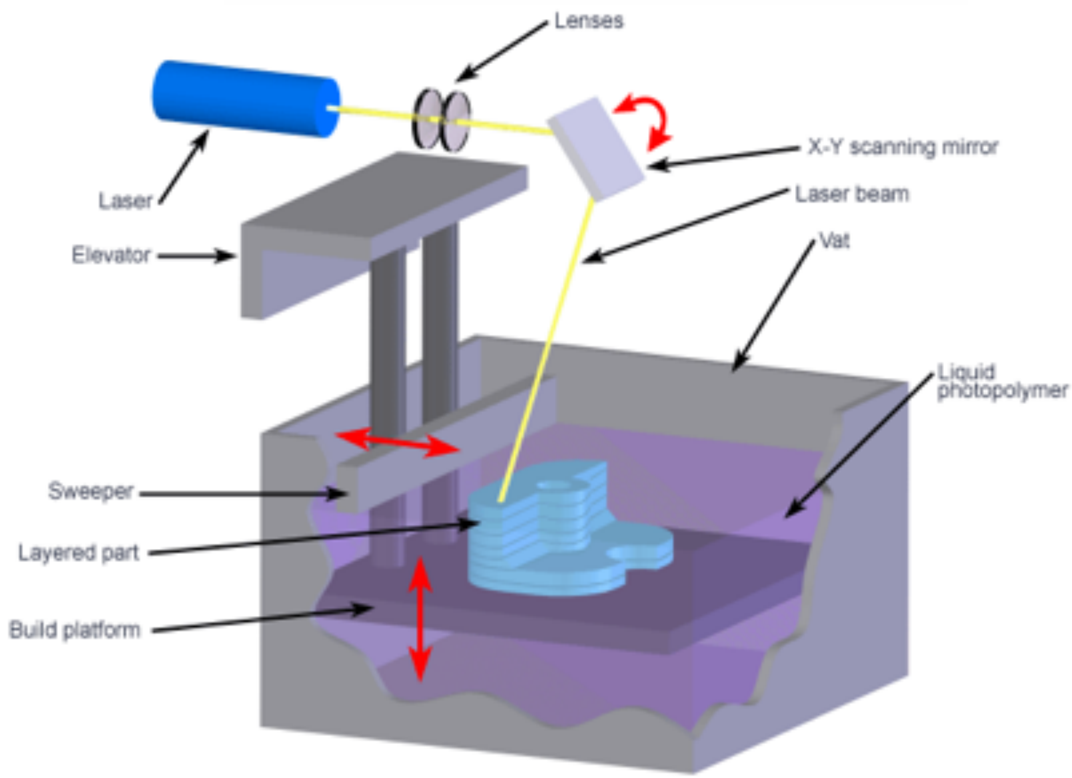
[11] Cotteleer, Mark. "3D opportunity: Additive manufacturing paths to performance, innovation, and growth." The Next Revolution: Additive Manufacturing Symposium . Deloitte Services. Southern Institute of Manufacturing and Technology, Florence. 1 Oct. 2014. Lecture.

constantly being invented and improved upon, so attempting to provide an accurate, holistic list of the different AM methods would result in a list rendered almost immediately obsolete. In order to show how broad of a term AM actually is, here is an incomplete list of current methods used within the industry: Fused Filament Fabrication (Fused Deposition Modeling), Robocasting, Electron Beam Freeform Fabrication, PolyJet Printing, Laser Engineered Net Shaping, Laminated Object Manufacturing, Stereolithography, Selective Laser Sintering, and Three Dimensional Printing. Because there are so many different methods, this research will only focus on three types of additive manufacturing systems: Stereolithography (SLA), Selective Laser Sintering (SLS), and Fused Filament Fabrication (FFF). This chapter first provides a brief definition on how these three systems work, then historical accounts on the systems, and finally market analyses of the entire AM industry.

Stereolithography (SLA) is a process that uses a laser to solidify photo-polymer liquids. Photo-polymer liquids are materials that transform from a liquid to a solid when exposed to specific kinds of light. SLA printing works by sinking a platform into a vat that contains photo-polymer resin material; the platform is then immersed into the vat just enough to create a thin layer of photo-polymer liquid that forms the object's base. After the platform is submerged, lasers outline the object's desired shape, creating a layer of hardened material. The platform then sinks down again, acquiring a new thin layer of photo-polymer liquid on top of what was previously shaped. See "Figure 1. The Apparatus of Stereolithography Printers" for more details.[12] If desired, the platform can move micrometers, making layers thinner than the width of a sheet of paper. Because the platform can move at such micro-levels, SLA can fabricate high

[12] Materialgeeza. *Stereolithography Apparatus.* Digital image. *Wikipedia*. 1 May 2013. Web.

Figure 1. The Apparatus of Stereolithography Printers



Source: Materialgeeza

quality, precise products. However, the downsides include that certain photo-polymers can create fumes that are toxic to breathe, and "photo-polymers are not as strong and durable as their thermoplastic cousins used in injection molding."[13]

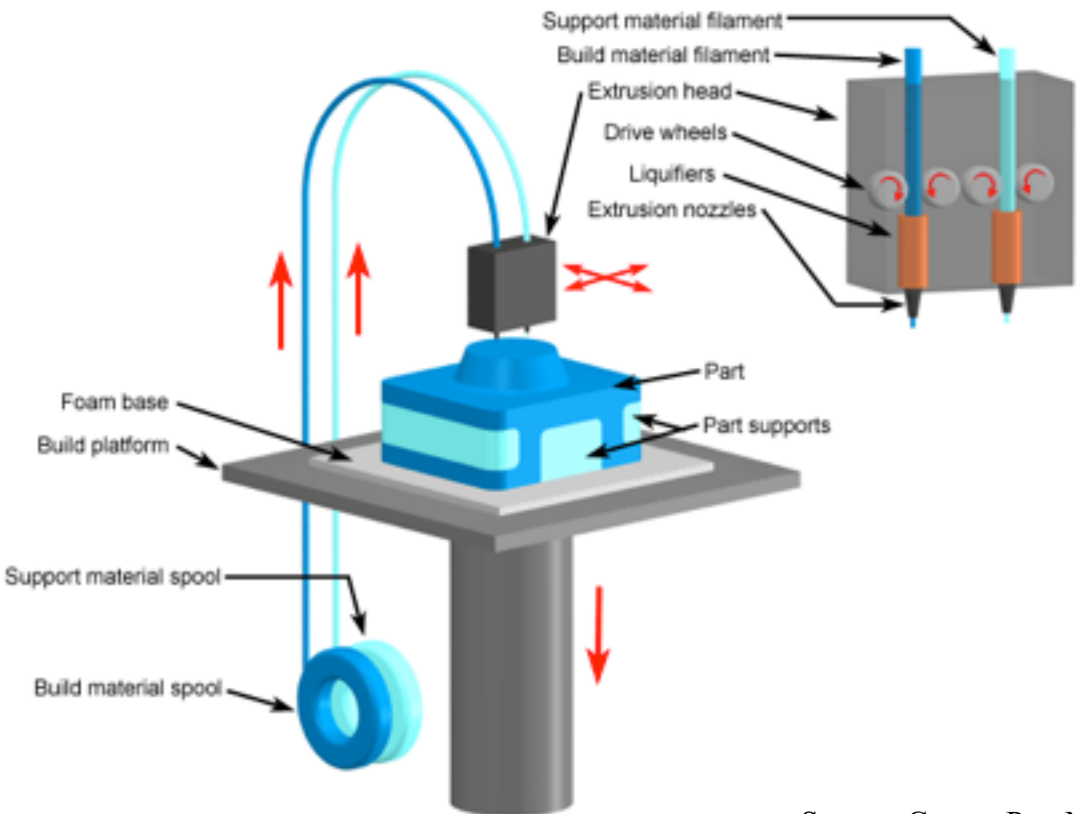
Selective Laser Sintering (SLS) is similar to SLA except instead of using liquid photopolymers, SLS printers use granular powders that solidify when a laser heats it below its melting point. SLS products are less likely to collapse while printing than SLA products, because the unexposed powder is used to support the unfinished print. Other advantages to SLS include that a lot of leftover powder can be recycled, and SLS materials are more versatile since many

13 Lipson et al. 74.

raw materials can be ground into powder form.[14] There are downsides including the fact that SLS products are not as smooth and the products typically end up being porous. Also, SLS can be dangerous and these printers are typically not suited for office use. For example, SLS printers need a sealed chamber filled with nitrogen, and this makes it very dangerous and possibly explosive.[15] A final problem to consider is how hot the SLS process is. When the products are finished printing, they can require many days to cool.

Fused Filament Fabrication (FFF) uses firmware files (a 3D-printer's built in software that orients the model for the build process) to calculate a path for printing. The printers deposit

Figure 2. The Apparatus of Fused Filament Fabrication Printers



Source: CustomPart.Net

[14] Lipson et al. 209.

[15] "The Benefits of Selective Laser Sintering." *Approto.* American Precision Machining. Web. 8 Apr. 2015.

raw material through print heads or nozzles, creating 3D products through successive layers. The printer extrudes small beads of material to form layers, and the material hardens immediately after being extruded. Like a regular 2D printer, FFF printers have an x and y-axis in which the printer deposits a layer of material. The nozzle also has a z-axis that it can move up and down on, creating 3D layers. See “Figure 2. The Apparatus of Fused Filament Fabrication Printers” for more details.[16] Although FFF printers typically require more time to print than most SLA and SLS printers, FFF have very little, if any, cooling time. A problem with FFF printing, however, is that the process requires support material to act as a framing structure, generated in order to hold the actual model in place while printing, similar to scaffolding. If a product’s shape is complicated and needs a lot of support while printing, the process will end up wasting a lot of material used to build these supports.

History of AM. The general public considers 3D printing cutting-edge technology, envisioned only in the last decade. Contrary to popular belief, the concept of 3D printing has actually been around for hundreds of years, and 3D printers have been around since the 1980’s. Over a hundred years ago, in 1859, Francois Willeme positioned cameras on a circular platform at different positions, for a complete representation of his subject in 3 dimensions.[17] Willeme then used his photographs to create data from which he used a pantograph attached to a cutter that then created a photo-sculptured model. This is a similar process used in 3D printing, called 3D scanning. 3D scanning collects data of a subject’s shape and dimension, using it to construct digital 3-dimensional models. Although the first crude digital 3D models would not appear until

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[16] *Fused Deposition Modeling (FDM).* Digital image. CustomPartNet. 1 Jan. 2008. Web.

[17] "1859 - The Year 3D Printing Hit the Mainstream." 3D Add Fab. 3D Additive Fabrication, Inc., 2 Jan. 2012. Web.

the 1950s, Willeme in many ways was a predecessor to 3D scanning, which carries a lot of importance within the AM industry.

SLA was the first 3D printer to be invented, and its invention began at the American chemical company DuPont. DuPont began researching the polymerization of specific chemicals in the 1940s and discovered photopolymers—the liquid material used inside SLA vats. In 1948, DuPont commercialized the first photopolymer resin, called Telfon TFE-flurocarbon resin.[18] Because of this discovery, various scientists began researching how to manufacture objects by solidifying these photopolymers. The first known attempt to create objects with the chemicals began in the late 1960s at the Battelle Memorial Institute in Ohio.[19] In May 1980, Hideo Kodama of the Nagoya Municipal Industrial Institute applied for a patent in Japan for his idea of three-dimensional modeling. However, because of difficulties in securing funds for research and development, the patent application process failed to proceed to the examination stage. In October 1980, Kodama published a paper entitled "Three-Dimensional Data Display by Automatic Preparation of a Three-Dimensional Model."[20] Here, his work is outlined, and his experiments were similar to the techniques now used in SLA. This paper is arguably the first evidence of an effective AM technique. Although Kodama's papers described the process, 3D Systems was the first to actually produce a successful additive manufacturing system. Charles W. Hull invented and patented the SLA process in 1983, then founded 3D Systems in 1986, and introduced the first 3D printer to the world, the SLA1, in 1987. After thorough testing, the very

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[18] "R&D History at the DuPont Experimental Station." *DuPont Science & Technology.* DuPont. Web.

[19] Wohlers, Terry, and Tim Gornet. "History of Additive Manufacturing." *Wohlers Report.* (2014): 27.

[20] Wohlers et al. 28.

first AM printer was sold in 1988. Hull was accredited to the National Inventors Hall of Fame in 2014 because of his SLA patent.[21] As of July 2014, 3D Systems grew to have a market capitalization of $5.9 billion.

SLS was invented in Austin, Texas at the University of Texas. In 1984, Carl Deckard, a senior at the University of Texas, began to plan his graduate school project. His project concerned the idea of using energy beams to melt particles of powder to create parts. After Deckard approached one of his assistant professors, Dr. Joe Beaman, with this idea, the two agreed to work together on the project.[22] While waiting for funds, Deckard discovered how to control lasers through computer processes, creating a custom board. After completing his masters, Deckard continued on to get his Ph.D and to keep working on the project. Their research ultimately lead The National Science Foundation to award Deckard and Beaman with a $30,000 grant to advance their technology.[23] Once the SLS process showed real improvement and other engineers, professors, and researchers joined, the team decided to create a private corporation. They named the corporation Nova Automation, and it became the first SLS company in the world. After struggling to procure funding, Dr. McClure, who did most of the fundraising for Nova Automation, became president. Dr. McClure renamed the company DTM Corp, and convinced Goodrich to fund DTM. With Goodrich's funding, in 1989, DTM was able to design the first successful commercial SLS printers in the world (Mod A and Mod B). In 1999,

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[21] Wohlers et al. 29.

[22] McLellan, Charles. "The History of 3D Printing: A Timeline | ZDNet." *ZDNet.* 1 Aug. 2014. Web.

[23] "Selective Laser Sintering, Birth of an Industry." *University of Texas.* Department of Mechanical Engineering, 30 May 2013. Web.

Goodrich sold most of DTM shares to ProActive Finance, which later sold the company to 3D Systems in 2001.[24]

The inventors of additive manufacturing seemed to all start blossoming between the three years of 1987 to 1989. FFF printing is no exception, as S. Scott Crump co-founded Stratasys Inc. in 1989. In that same year, Crump developed the first Fused Deposition Modeling (FDM) system.[25] The reason this research uses the term “fused filament fabrication” instead of FDM is because FDM is a trademarked term, so hobbyists and researchers typically use FFF in their writing. In early 1992, Stratasys introduced the first commercialized FFF printer, the 3D Modeler, shipping units later that year. Stratasys grew quickly, from selling six units in 1992 to a total of 1582 units in 2000.[26] FFF printers are the most popular commercialized printer, the reason for their growth and popularity being attributable to various factors. For one, FFF printers are safer and easier for office use than most other forms of AM. Other important factors include the *RepRap* project and the expiration of FDM patents.

Dr. Adrian Bowyer founded the *RepRap* project, in March 2005. Bowyer was very interested in the 3D printing industry, but he felt that the price for the devices were too steep.[27] Because of this the *RepRap* project began as a British initiative to create an affordable 3D printing machine that could self-replicate; Bower wanted to create a cheap 3D printer that could print out most or all of its own parts. Imagine buying an affordable printer and then being able to

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[24] “Selective Laser Sintering, the Birth of an Industry”

[25] Lipson et al. 58.

[26] Chua, Chee Kai, and Kah Fai Leong. Rapid Prototyping Principles and Applications. 2nd ed. Vol. 1. Singapore: World Scientific, 2003: Print. 124.

[27] "About RepRap." RepRap. Web.

print out a new one for your friends at an even lower cost. In 2008, *RepRap* successfully created "Darwin", an FFF printer that could create half of its rapid-prototyped parts. This increased 3D printing's popularity and consumer awareness, because *RepRap*'s main aims were to create cheaper printers for the masses and to keep their information and designs open source. Open source designers promote universal access and free licenses to a product's blueprint, which is the opposite of proprietary designers who keep product's designs locked down with patents and licensing. Understanding how open source works and its importance within the movement is key in understanding why 3D printing grew so rapidly from 2008 to 2010. Further, it is important to point out that in 2008 FDM's patent expired, and in 2014, SLS's patent expired. Although the additive manufacturing process has slowly been gaining traction, new technologies, cost savings, and patent expirations give 3D printing a greater potential to amplify market growth.

Market Analyses. Additive manufacturing is used in a broad amount of industries including automotive, dental, high tech, aerospace, and medical products. Currently, prototyping continues to "dominate the reasons why enterprises pursue 3D printing, with the opportunity of improving new product development and time-to-market being long-term goals."[28] The main uses of additive manufacturing are to improve quality, reduce costs, and to increase flexibility within designs. Currently SLA is only cost effective for concepts, design and engineering and prototyping. Meaning, SLA is not yet cost effective for low volume productions and mass productions. However, for designing new products, SLA is popularly used within the manufacturing industry to cut costs, waste and time. SLS and FFF on the other hand, have made

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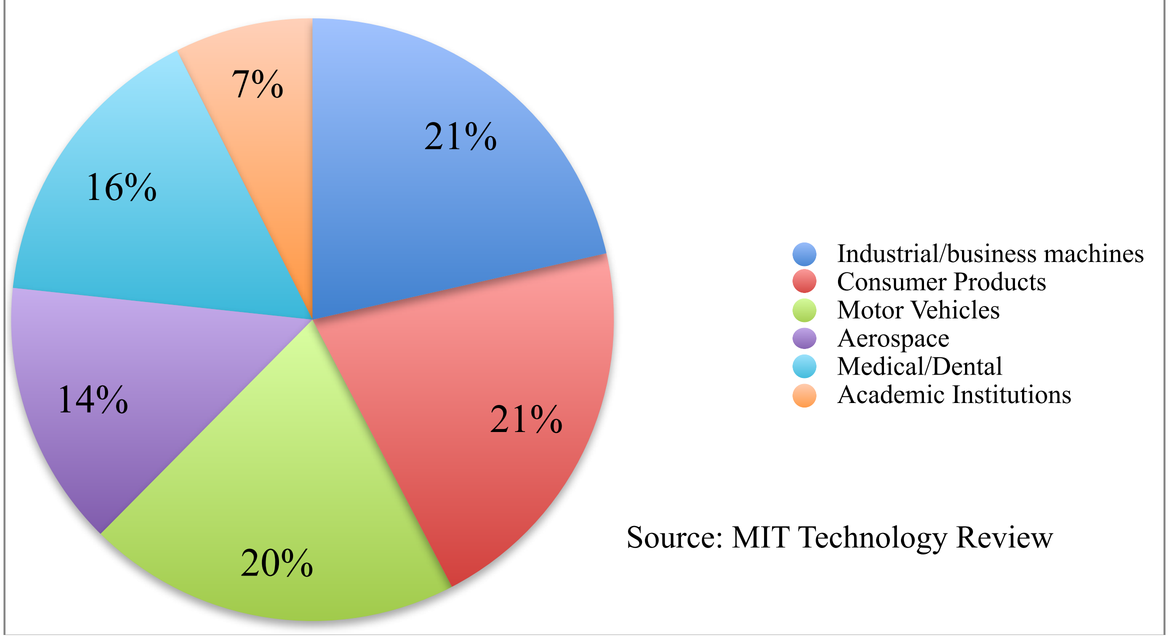
[28] Columbus, Louis. "2015 Roundup Of 3D Printing Market Forecasts And Estimates." *Forbes.* Forbes Magazine, 31 Mar. 2015. Web.

it to the low volume production phase, and are used cost-effectively to produce a restricted amount of products. See “Figure 3. Industries Embracing Additive Manufacturing” for a breakdown on which industries are investing in additive manufacturing printers.[29]

When looking at what materials are used most within the industry, the answer is currently plastics. Plastics accounted for an “estimated 80% of industry sales, and metals (which largely

Figure 3. Industries Embracing Additive Manufacturing



became available in 2009) account for around 6%”[30] The materials that are the most developed for prototyping, tooling and piloting include plastics (polystyrene and ABS) specific metals (steel, aluminum, nickel alloys, and copper), bonded plaster, and paper. For manufacturing, titanium, nylon, and sand are matured materials ready for production. Materials still in early development but which show an enormous amount of potential for future applications include

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[29] "The Growing Business of Additive Manufacturing." *MIT Technology Review.* Web.

[30] Cotteleer, Mark

concrete, living tissue, carbon fiber-reinforced plastics, glass, food and clay. For example, a "Sugar Lab" at 3D Systems creates personalized, edible wedding toppers.[31] The AM food industry still needs major development, but it's an exciting novelty for now. Theorists and researchers imagine having meals printed and personalized for specific dietary needs. The US Military is currently investing in "mobile production facilities that can manufacture parts in the combat zone to get rarely requested, but vital, replacement parts quickly to the field." [32] This helps localize 3D printing and reduces players within manufacturing, cutting down the supply chain.

To understand and predict the growth of 3D printing, there are platforms dedicated to the industry that provide research and data. They do this by tracking the location of printers using their sites, the amount of material being used, the amount of printers, and the amount of print time. The largest "3D Printing Platform" is 3D Hubs. Just to understand exactly what a 3D printing platform is, look at how 3D Hubs defines itself as:

> A collaborative production platform for 3D printer owners and 3D makers. We are on a mission to make 3D printing accessible to everyone by unlocking the world's idle 3D printers, facilitating transactions between 3D printer owners (Hubs) and people that want to make 3D prints (makers). 3D Hubs is the world's largest network of 3D printers with over 2,500 printing locations across 80 countries (and counting), helping people print 3D customized products locally every day.[33]

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[31] McFarland, Matt. "5 Amazing Ways 3-D-printed Food Will Change the Way We Eat." *Washington Post.* The Washington Post, 28 Jan. 2015. Web.

[32] Cotteleer, Mark

[33] "3DHubs's Thingiverse Profile." About 3DHubs. ThingiVerse. Web.

Because 3D Hubs is the world's largest network of this kind, looking at their data is useful in understanding the growth of the 3D printing industry. Their growth trends in printer listings, in 2014 alone, increased by 200%.[34] That's a dramatic increase of printers in a single year. If printer listings continue to rise, people will have more access to local printers, which in turn would make AM manufacturing a local process. The recent growth in the AM industry is nothing short of drastic. In 2007, only 66 printers were sold in the United States. Less than five years later, that number rose to 23,265 printers sold in 2011. 2010 was a magical year for the AM industry, as printers began to increasingly sell on a commercial level as well. Shapeways, another 3D printing platform that acts as 3D printing marketplace and service, allows users to upload their 3D printable design files and print their own or other users' designs. They released an info graph showing strong growth in income, items printed, and members in 2011. The global AM market went from $1.1 billion in 2009 and reached to $3.0 billion in 2013.[35]

Improving printer speeds, the widening range of materials, new forms of AM methods and substantial increase in the number of vendors has accelerated the growth of the market. Also, a huge part of the AM or "maker" industry is the idea of open-source markets. Forecasting the AM market proves more difficult, as research analysts predict the market will range from $7 billion to as high as $21.3 billion by 2020. All research firms are in agreement, though, that the AM market is on the rise. Sophic Capital created a chart below "Figure 4. Predictions of Additive Manufacturing Growth." This compares various firms' market predictions, charting a wide range

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34 "3D Printing Trends April 2015." *3D Hubs*. 2015. Web. 10 Apr. 2015.

35 "3D Printing Trends April 2015."

of market predictions.[36] By using data from the Wohlers Report 2014, "Figure 5. Worldwide 3D Printing Industry Forecast, Billions" shows previous and current forecasts made by the firm.[37]

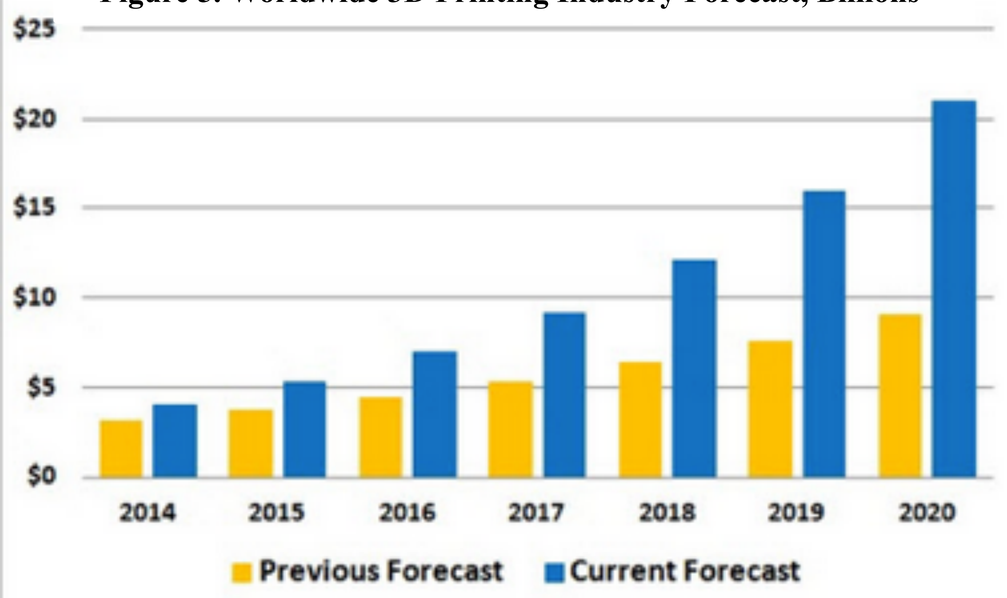
Figure 4. Predictions of Additive Manufacturing Growth

RESEARCH FIRM	YEAR ($ Billions) 2013	2014E	2015E	2017E	2018E	2020E	CAGR	CAGR Period
AMR	$2.3					$8.6	20.6%	2013-2020
Canalys	$2.5	$3.8			$16.7		45.7%	2013-2018
CCS Insight	$1.2				$4.8		33.0%	2013-2018
Freedonia				$5.0				
Gartner			$1.6		$13.4		103.1%	2015-2018
IBISWorld *		$1.4					15.7%	2014-2019
IDC							29.0%	2012-2017
Wohler	$3.1				$12.8	$21.0	33.0%	2013-2018

* U.S. market only

Source: Sophic Capital

Figure 5. Worldwide 3D Printing Industry Forecast, Billions



Source: Wohlers et al.

[36]"3D Printing— The Education Sector Is on the Cusp of Adoption." Sophic Capital. 16 Mar. 2015. Web.

[37] Wohlers et al. 28.

Chapter 2: From Assembly Lines to Keyboards

"Our world relies on manufacturing. All material goods begin as raw materials, are developed into products, and are used and then discarded. But for centuries, the manufacturing process itself has evolved into one in which the final product is constrained by the tools one uses to produce the product. Complex shapes and routine customized parts can be expensive and, in some cases, impossible to produce using traditional manufacturing techniques."
-Olga S. Ivanova and Thomas A. Campbell

Additive manufacturing machines give inventors an option to create complex products that would have been too expensive or impossible to create through traditional methods. This is because AM processes liberate manufacturers from being constrained by their tools. No new tools or materials are required in the design phase of additive manufacturing, because design is done digitally, through CAD files. Designing a product on a CAD file and changing the shape, color, and design requires little time and no money—when using a free CAD system. Unlike traditional manufacturing techniques, the design phase does not require nuts, bolts or a whole lot of money to create a molding block and/or assembly line.

For example, if an inventor wanted to create a teapot using an AM printer, her first printed teapot would cost her the same amount as her hundredth teapot. However, with traditional manufacturing processes, her teapot would cost less the more teapots she created. Because there are free CAD programs and the cost of printers is decreasing, a lot of financial and time restrictions to enter the teapot industry would be removed for her through AM. This means that 3D printing designers or as they like to call themselves, "makers," have fewer obstacles to enter the AM market. In other words, there are fewer barriers to enter the AM industry, which makes the growth discussed in the previous chapter very exciting.

Still, technologies on the rise, especially potentially disruptive technologies, deserve our critical attention. There must be more research done on how 3D printing offers solutions to climate change's problems, how it compares to traditional manufacturing, and its main environmental concerns. Questions we need to be asking now include, what environmentally positive inventions are additive manufacturing offering to the masses? And on the other and more pessimistic hand— what devastating inventions and environmental damage will the future of additive manufacturing bring? There is no way to answer these questions without first analyzing 3D printing's current environmental impact. This chapter outlines and provides groundwork in defining the methods and criteria needed to create an accurate understanding of 3D printing's environmental impact. The research in this chapter also defines essential environmental regulation principles to reduce 3D printing's environmental impacts. By outlining these standards, this chapter provides a foundation for the following chapters. The next chapters use the methods and criteria in this chapter to assess 3D printing's current environmental impact, the regulation needed to reduce that impact, and what the future of 3D printing has to offer the world.

Creating Accurate Footprints. Ecological footprints, carbon footprints, I=PAT models, and life cycle assessments are calculation methods used in case studies to develop an understanding of environmental impacts. The next chapter analyzes case studies that use these methods to evaluate the 3D printing industry's environmental impact. Because each methodology has its advantages and disadvantages, researchers must have a careful understanding in how they work. In order to fully understand the AM's environmental impact, there must be a complete understanding of how environmental data is processed. This section defines these models in order understand how they are useful in analyzing sustainability claims made by researchers who study the AM industry. Understanding the advantages and disadvantages of each of these assessments will be beneficial in creating an accurate analysis of the case studies presented in the following chapter.

Mathis Wackernagel and William Rees created the concept and calculation method of "ecological footprint."[38] An ecological footprint is a standardized measure of the demand on natural ecosystems. Ecological footprints can be calculated at a variety of scales; they have been used to measure a specific activity, person, population, nation, globe, and specific industries, like the 3D printing industry. Ecological footprints calculate this demand by assessing the land and marine area required to produce the resources and absorb the corresponding waste. Per capita ecological footprint is a tool that educates people about over-consumption, by demonstrating the amount of resources they actually use. Ecological footprint is measured in global hectares per capita, with one global hectare representing a unit of area equal to 100 square meters (2.471 acres).[39] So when looking at AM's ecological footprint, the subjects that are examined are important. For example, if two scientists examined the ecological life of the same type of FFF printer, but they used two different subjects, their ecological footprints for the same FFF printer would be very different. Especially if one subject was conservative and the other was wasteful. The conservative user who recycles all the machine's parts and materials would have a lower ecological footprint than a wasteful user that tirelessly prints useless objects and throws the machine in a landfill.

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[38] Wackernagel, Mathis. "Ecological Footprint and Appropriated Carrying Capacity: A Tool for Planning Toward Sustainability." *School of Community and Regional Planning* (1994). Print.

[39] "Glossary." Footprint Network Org. Global Footprint Network. Web.

A carbon footprint is the set of greenhouse gas (GHG) emissions that a person, product, or industry produces.[40] GHGs include water vapor, carbon dioxide, methane, nitrous oxide, ozone, and chlorofluorocarbons. A greenhouse gas absorbs infrared radiation, and releases it, radiating heat in all directions. GHGs in the atmosphere prevent heat from escaping into space, consequently contributing to climate change. Carbon footprints are important to measure when looking at how an industry affects the environment. For example, looking at the amount of GHGs used by the AM industry will show how the AM industry contributes to climate change. However, looking at the carbon footprint is simplistic in assessing the environmental impacts of the AM industry. This is because carbon footprints only analyze the release of GHGs. Releasing greenhouse gases is not the only way an industry can negatively impact the environment.

I=PAT is another way to measure the impact of a specific human activity on the environment. I stands for human impact on the environment; P stands for population; A stands for affluence; and T stands for technology.[41] Barry Commoner argued that environmental impacts were caused by changes in the environment following technology changes after World War II. Paul Ehrlich and John Holdren argued that all three factors (population, affluence, and technology) are important in understanding environmental impact, emphasizing population growth. Through discourse, the three scientists created the I=PAT algorithm.[42] The P in the equation, for AM, could represent all of the users of 3D printers. This is difficult to define, especially because of the *RepRap* movement. The number of printers that exist in the globe is

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[40] "What Is a Carbon Footprint- Definition." *Time for Change.* Web.

[41] Gillaspy, Rebecca. "What Is IPAT? - Factors of the Human Impact on the Environment." *Study.com.* University of Phoenix. Web.

[42] Gillapsy, Rebecca.

unknown and can only be estimated, because many makers built printers with their own hands. The P could also represent the clientele and manufacturers of a specific brand, like Makerbot or 3D Systems. P represents the population of an area. For I=PAT models, the population scale matters. According to I=PAT, the increasing numbers of users in the industry has a proportional effect on resource use, pollution use, and land use. Affluence in the I=PAT model represents the average consumption of each person in the population. When looking at affluence for AM, analyzing the amount of material and electricity an average user consumes is important to look at as well as the "population" of the industry. Finally technology represents how resource intensive the technology is. By analyzing the impact involved in creating, transporting, and disposing the goods, technology represents the environmental impacts of creating a specific technology. A problem with the I=PAT model is that it credulously assumes that population, affluence and technology are independent of each other, when in reality there are at least seven interdependencies that exist.[43]

Life-Cycle assessment (LCA) is a technique similar to measuring an industry's ecological footprint, in which it assesses the environmental impacts associated with all the stages of a product's life from cradle-to-grave[44]. LCAs prevent narrow outlooks on environmental concerns by compiling all relevant energy and material inputs, evaluating potential impacts associated with identified inputs and releases, and interpreting results to help make informed decisions. The case studies that use LCA will be the most beneficial in understanding AM's environmental impact, because all environmental impacts are considered through LCA. The only problem with

[43] Alcott, Blake. "Impact Caps: Why Population, Affluence and Technology Strategies Should be Abandoned." *Journal of Cleaner Production*: 552-60.

[44] "Life Cycle Assessment (LCA)." *EPA.* Environmental Protection Agency. Web.

LCA is that it ignores the potential of the AM industry in becoming a cradle-to-cradle industry. The differences between cradle-to-grave and cradle-to-cradle industries will be described in the next section.

After looking at famous models of measuring an industry's environmental impact, an outline of the criteria is needed to wholly understand AM's environmental impact. Beginning with the manufacturing of the printers to the disposal, there needs to be a detailed assessment of the various types of machines, their ecological and carbon footprints and their LCA. The next chapter will examine case studies that assessed SLA, LS, and FFF printers in these ways, but will also point out to areas in which more scientific research needs to be done examining the printers. The printers themselves need to be examined and how and where they are manufactured, how and where they are bought, how much energy they consume, and how they are disposed of. There then needs to be an analysis of how much of a toll these factors take from the environment. The purpose of the machine is also important to look at: how many printers are being sold for essential goods and services, and how many are for convenience or luxury goods? This is important to analyze, because if the goods are useless, they will be readily trashed. Next, what material is used during the printing of products and how that compares to traditional manufacturing, where and how are the materials being disposed of, how much of the material is being disposed should also be looked at.

Reshaping Manufacturing: Ecological economics is an interdisciplinary field of academic research that addresses how human economies and the Earth's ecosystems are intertwined. The difference between ecological and environmental economics is the treatment of economy as a subsystem of the ecosystem, stressing the need to preserve natural capital. As such, ecological economists reject the proposition that natural capital can be substituted by human-made capital.[45] In order to fully understand how we can reshape the AM industry to minimize the environmental impacts, we must have a perspective in which we value the environment more than we value capital. For this reason, when the research discussing how to reshape the AM system in an ecologically *ideal* fashion, ecological economics is used more so than environmental economics.

However, this research does not simply provide ideal treatment, Chapter 4 also provides realistic sustainable business practices, in which the American AM industry can minimize its waste while also cutting costs and attracting capital. Sustainable business concepts involve creating innovation within a company or industry that moves its products and services towards less waste production. Collaborating the knowledge of how to reduce waste and remain sustainable is an important aspect of sustainable business, because the sharing of this vital knowledge helps other businesses with bigger footprints. Continuous process improvement is also important for sustainable businesses, because employee awareness of a company helps integrate new and improved processes for other businesses. Without constant surveying, the previous strategies cannot be practiced. For example, if continuous improvement does not occur, then innovative technology will not be adapted by the company either. Sustainability reporting is important in implementing a monitoring system to keep the company true to its claims.

Biomimicry is another potentially great tool for reshaping industry to be more sustainable, and its principles can especially be applied to AM. Biomimicry imitates nature's models, systems and elements in order to solve complex human problems, like reducing

[45] Campiglio, Emanuele. "Ecological vs. Environmental Economics." *Nef Economics,* 8 July 2011. Web.

environmental impact.[46] There are many ways in which the 3D printing industry already does this, which the next chapter will reveal. One aspect of biomimicry is cradle-to-cradle recycling. Cradle-to-cradle design is an approach similar to how nature circulates nutrients in healthy, safe metabolisms, enriching the ecosystems with its organic waste. The idea behind cradle-to-cradle design is to change the way we make things. Instead of reduce, reuse, recycle, in cradle-to-cradle design, when products are discarded, the process of throwing them away or recycling creates or re-births a new product in itself. This is different than recycling because recycling encourages the ideas of down cycling and cradle-to-grave models.[47] Basically the difference between recycling and cradle-to-cradle recycling is the fact that “reduce, reuse, recycle” is a linear system. However, “cradle-to-cradle” is circular, and in that the same product is being produced after it is disposed of. AM manufacturing makes this possible with certain reusable materials and Recyclebots discussed further later on. Finally, when thinking about how to improve the AM industry we must think of the pools of resources available to adapt to environmental change. We must think about the different solar powered AM printers and how these compare to the fossil powered machines. We must think about how different materials being invented can provide environmental change. We must also consider how these can impact the environment in a negative way.

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[46] Clark Howard, Brian. "Improving 3-D Printing by Copying Nature." *National Geographic.* National Geographic Society, 7 July 2013. Web.

[47] McDonough, William, and Michael Braungart. *Cradle to Cradle: Remaking the Way We Make Things.* New York: North Point, 2002. Print.

Chapter 3: Prototyping The Environmental Impacts

"Only one study was found to have measured multiple kinds of ecological impacts together to balance the effects of material use, waste, toxins, and other factors against energy use in a life-cycle assessment ("LCA") with combined single-score measurements, comparing several 3D printer types. That study was from 1999, so even without the current project's new focus on materials, the older study should be updated for changes in 3D printer technology, available 3D printing materials, and LCA tools." -Jeremy Faludi et al.

As argued in the previous chapter, there must be an assessment of case studies that analyze the environmental impacts of the machines and materials used in 3D printing. First by evaluating the machines, we will compare their environmental advantages and disadvantages. Next, there needs to be an analysis of the different materials used in the AM industry.

Evaluating the Machines. Comparing the impact of SLA, SLS, and FFF is important. For looking at FFF's environmental impact, this research will examine a case study done by Dr. Pearce and Megan Kreiger and another case study done by Faludi et al. Both take a LCA approach to examine FFF's environmental impact. In Dr. Pearce and Megan Kreiger's study titled "Environmental Life Cycle Analysis of Distributed Three-Dimensional" the two scientists used an EcoInvent database program to cumulate data on the energy demand and global warming potential for a RepRap printer. Their findings indicated that a RepRap 3D printer has less environmental impact than conventional manufacturing because of its "ability to adjust the internal fill of a product, the ease of adapting to PV power, the ability to further reduce environmental impact using improvements in energy efficiency of printing technology and recycling filament"[48] In the next section, when we evaluate materials, this will be an important case study to examine as well. Pearce and Kreiger found that the energy demand on

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[48] Kreiger, Megan, and Joshua M. Pearce. "Environmental Life Cycle Analysis of Distributed Three-Dimensional Printing and Conventional Manufacturing of Polymer Products." ACS Sustainable Chemistry & Engineering (2013): 1516.

manufacturing polymer products can be reduced by 41-64% when using AM instead of traditional manufacturing processes. The energy demand can be reduced even further—up to 74%— when using solar powered printers.[49]

A case study done in 2015 by Faludi et al. reveals important environmental information about FFF printers as well. Their study analyzed six different 3D printers and used different materials to determine if material drove sustainability or if other factors dominated. Their study examined AM through environmental impacts including fossil fuel depletion, natural land transformation, agricultural land occupation, freshwater ecotoxicity, freshwater eutophrication, climate change ecosystems, particulate matter formation, human toxicity, climate change human health, metal depletion, urban land occupation, marine ecotoxicity, terrestrial ecotoxicity, terrestrial acidification, ionizing radiation, photochemical oxidant formation and ozone depletion. For FFF printing in ABS, Faludi et al. discovered that "just three to five categories of ecological impacts dominate."[50] Those five impacts that dominated included "fossil fuel depletion, climate change damage to human health, particulate matter formation, climate change damage to ecosystems, and human toxicity, in order."[51] They discovered that electricity was the largest environmental impact in the LCA of FFF printers. As seen in Dr. Pearce's study, electricity can be minimized if using solar powered printers, and electricity also can decrease if fill capacity is minimized. In another case study done by Faludi, "Comparing Environmental Impacts of Additive Manufacturing vs Traditional Manufacturing via Life-Cycle Analysis,"

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[49] Kreiger, Megan and Joshua M Pearce. 1511.

[50] Faludi, Jeremy et al. "Does Material Choice Drive Sustainability of 3D Printing?" *International Journal of Mechanical, Aerospace, Industrial and Mechatronics Engineering* 9.2 (2015): 147.

[51] Faludi et al.

Faludi examined six different machines through a cradle-to-grave LCA. called "Comparing Environmental Impacts of Additive Manufacturing vs Traditional Manufacturing via Life-Cycle Analysis." Although they examined six different 3D printers, FFF machines "scored so well that even at low utilization, it is nearly as sustainable as the other machines running at maximum utilization." [52] All LCA done by the different researchers found that FFF has the potential to be highly sustainable, as it maximizes material savings, no tools, moulds or punches are needed, time-to-market reduction, and the advantage of controlling the density of final parts.

A study done on Selective Laser Sintering by Petrovich et al. in 2011, found that raw material can be reduced up to 40% compared to subtractive technology. Further, "95 percent to 98 percent of the remaining material (Powder that is not fused) may be recycled."[53] In this way, Selective Laser Sintering is extremely valuable for reducing materials and waste. However, sadly, there are gaps of information publicly available that describe SLS in comparison to other machines, specifically their electricity use. Since, Faludi suggests in his research that material choice does not drive sustainability of 3D printing as much as electricity does, more research done on different aspects of SLS needs to be done for a full examination of SLS to be made. Telenko and Seepersad said specific energy consumption is difficult to prescribe for SLS, "because of the variance in build density and height" within the machines.[54] The study found that

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[52] Faludi et al. "Comparing Environmental Impacts of Additive Manufacturing vs Traditional Manufacturing via Life-Cycle Analysis." Mechanical Engineering, University of California. Berkley (2015): 14.

[53] Petrovic et al. "Additive Layered Manufacturing: Sectors of Industrial Application Shown through Case Studies", *International Journal of Production Resarch,* Vol. 49 No. 4 (2011): 1070.

[54] Telenko, C. and Seepersad, C. "A Comparison of the energy efficiency of selective laser sintering and injecetion molding of nylon parts", *Rapid Prototyping Journal,* Vol. 18 No. 6 (2012): 475.

SLS energy consumption is time-dependent. Cooling time was the greatest contributor to the energy used within the SLS process.

The main disadvantage to Stereolithography has been found that changing materials in a product takes a substantial amount of time. The stigma of “rapid prototyping” within the additive technologies is bad, because currently, 3D printing can take hours to print an object. For example, the Makerbot printer takes eighteen minutes to print out a toy shark smaller than a single AA battery. Similarly, SLA cannot produce multi-color or material products without changing one type of resin to another, which requires a lot of time. However, these are just these specific machines. Keep in mind that there are time-to-market reduction is made when created complex objects. This will be explained further in the next section.

Evaluating the Materials. When it comes to 3D printing, the most popular material used is plastic. There are many kinds of plastic that come in spools with spaghetti-like string of plastic wheels. The currently most widely used plastic is Acrylonitrile butadiene styrene (ABS), which is a plastic derived from oil-based resources, natural gas and petroleum. Heating up ABS can produce fumes of acrylonitrile, which is concerning because acrylonitrile could be a human carcinogen. Additionally, alcohol produces a reaction similar to heating when mixed with ABS, producing hazardous carcinogen risks to humans if they drink out of cups made with ABS. ABS should also not be used for medical implants, as the body produces heat necessary for a reaction. In order to produce one kg of ABS resin in Europe, 26.48 kWh are expended. For using ABS in a 3D printer, ABS has a high melting point and needs to be printed on a heated surface (expending more energy during print). The biggest problem with ABS is that it is not biodegradable. This means that if an ABS product is not recycled, the plastic will remain in the environment forever. The problem with plastics not biodegrading was revealed when Charles Moore discovered "The Great Pacific Garage Patch," a region in the Northern Pacific ocean slightly smaller than the state of Texas filled with "a floating tangle of discarded plastic." Despite ABS negative environmental impacts, ABS is the most popular plastic used in consumer level 3D printing. ABS popularity is because of its sturdiness and cheap value. Although it has a high melting point, this is also a positive aspect of ABS, because a printed object will be harder to melt if left outside on a hot, summer day. Other benefits to ABS include the fact that ABS has a longer lifespan than PLA and it is recyclable (PLA is recyclable as well).

Polylactic acid or PLA is a biodegradable plastic extracted from renewable resources such as corn starch, soy, sugarcane, or tapioca roots. PLA has a higher print speed (which reduces the energy needed to print). PLA does not require a hot surface, but instead can have a cold surface while printing. There are no harmful fumes throughout the printing process, and the plastic is not only recyclable, but it will not end up in the Great Pacific Garbage Patch, if someone forgets to recycle. The problems with PLA plastic is that it can deform if heated past a certain point, the plastic is less sturdy than ABS, and more expensive than ABS. Figure 6 "Data Values: Emission Values in Global Warming Potential" shows a chart created by analyzing a case study on the differences of GWP between ABS and PLA at a 25% fill.[55] When printing ABS using non-renewable electricity, PLA produces .19 kg of CO2, and ABS produces .34 kg of CO2. This clearly shows that when comparing the two plastics' carbon footprint, PLA wins. The two plastics are compared further in the chart when the printer uses renewable energy at 25% fill.

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[55] Kreiger,and Pearce. 1513.

PLA has a GWP of .09 kg of CO2, while ABS nearly doubles that amount with 0.17 kg of CO2.

Data Values: Emission Values in Global Warming Potential (GWP) in kg CO2 eq

Emission Values to Manufacture a Block of Plastic						
TRADITIONAL MANUFACTURING			REP-RAP (FFF) 3D-PRINTING			
	Non-Renewable		Non-Renewable		Renewable	
Fill %	PLA	ABS	PLA	ABS	PLA	ABS
100%	0.26	0.44	0.35		0.19	
25%			0.19	0.34	0.09	0.17
10%			0.14		0.07	
5%			0.12		0.06	
0%			0.11		0.05	

Figure 6. Data found from Kreiger and Pearce's Case Study.

Even when using renewable energy as a power source, ABS still maintains a larger carbon footprint than PLA.

Fill and Complexity Options are also important because as we stated before, in traditional manufacturing, the more intricate a design, the more expensive a product. For additive manufacturing, the skill, time, and cost to print is not affected by the intricacy of a design. 3D printers can cost effectively create intricate products that reduce weight, last longer, and require less assembly, which in turn minimizes GHG emissions, energy consumption, and overall manufacturing costs. That is why Figure 6 does not show various fill options for the traditional manufacturing columns. Instead, the only option for traditional manufacturing is 100%. Take note that when comparing traditional manufacturing with FFF printing, if the fill is the exact same, traditional manufacturing has a lower carbon footprint. However, most 3D print jobs don't use 100% fill, as this is a waste of resources and money. So, the fact that FFF printing can reduce carbon emissions up to 64% is a great environmental advantage to 3D printing.

Because complexity is free, design optimization becomes a more viable option. Figure 7 shows two versions of a hinge for a jet-engine cover[56]. The one in the background was made with conventional manufacturing methods, while the intricately shaped hinge was made using LS technologies. The 3D printed hinge weighs half as much, which reduces nearly 40% of CO2 emissions over a whole life-cycle, due to the weight saving and the LS ability to save more titanium material than traditional manufacturing methods.[57]

Figure 7

Source: Stuart Nathan

A claim by the industry is that because AM is additive and not subtractive, there is a huge difference in waste byproduct, and that AM wastes no material. However, this is not entirely true, especially when looking at FFF printers. FFF printers require support material, which was explained in Chapter One. For hollow objects, print jobs need more support and those prints are particularly wasteful. Especially when the support material is non-biodegradable. Atkins study

[56] Nathan, Stuart. "Printing Parts." Technology Review. MIT, 23 Aug. 2011. Web.

[57] Lipson et al. 204.

found that “40 percent of excess raw plastic powder was re-usable in laser print jobs while 60 percent typically got dumped into the landfill.”[58] However, as noted before, the fill option and complexity options for AM are a huge environmental benefit. If a maker decides to be economical with her materials, she can still reduce waste, by reducing the fill option, weight and material used. However, regulation needs to be seriously considered in order to make sure makers are conservative and not wasteful.

Chapter 4. Attracting and Regulating Capital

> “3D printing opens up yet another new channel of plastic manufacturing. To become a greener form of manufacturing, 3D printing technologies need to embrace new, eco-friendly raw materials.”
> -Lipson and Kurman

In order for 3D printing to develop properly there are challenges the industry must face in the near future. 3D printing will be examined through the interdisciplinary approach, Industrial Ecology, as a promising area to help society realize methods discussed in Chapter 2. An Industrial Ecology (IE) study seeks to model the material flows of industrial processes to make modern society function by managing the planet’s supply of natural resources and managing waste disposal.[59] While in the previous chapter, the present footprint was examined, here, the potential footprint will be examined. Regulation treatment will also be provided. Discovering what the 3D printing industry is offering to the future of manufacturing, and if these offers are parallel to the promises of an industrial ecology.

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[58] Lipson et al. 203.

[59] “Introduction to Industrial Ecology." Indigo Development, 2005. Web

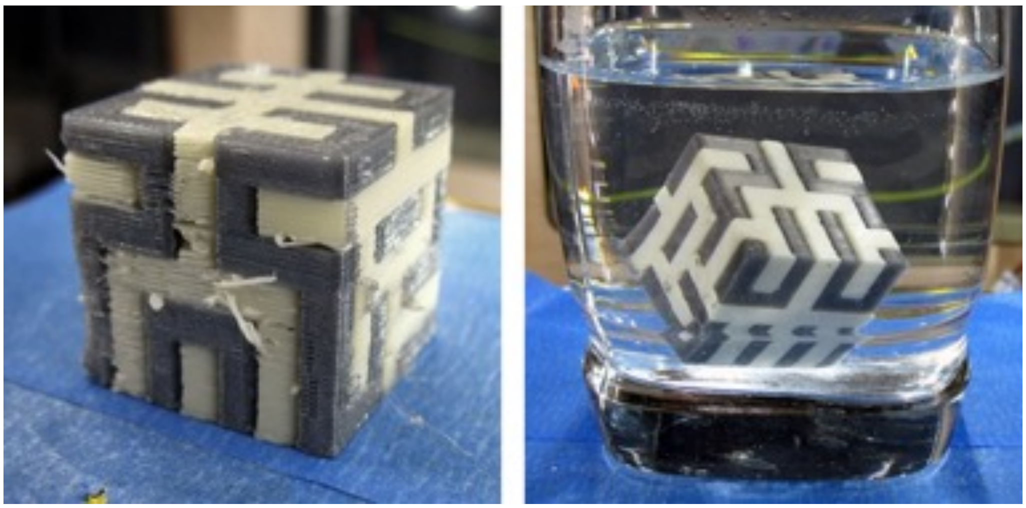
A environmental problem addressed in Chapter 3 was waste disposal. Although printers minimize waste in comparison to traditional manufacturing, waste is a problem that the globe must address if we want to have a sustainable industry. Further, the fact that plastic and non-biodegradable plastic is currently the most popular material used in the AM industry must be addressed. Landfills are a problem and so is dumping waste in the ocean. There are garbage patches being created in the Pacific ocean. Garbage patches are collections of litter that ends up in the oceans covering large spans. The Great Pacific Garbage Patch, also known as the Pacific trash vortex, is close to the size of Texas.[60] Although the amount of waste produced by the AM industry would only account to a football field in comparison to traditional manufacturing, the irresponsible nature of disposing non-biodegradable plastics needs to stop. Nations also need to take responsibility to provide funding and clean up plastic waste. The durability of plastics ends up destroying marine ecosystems. If the AM industry does not take a stand in regulating their waste use, the industry in no way will be positive for the environment. Until government funding and regulation is made on the use of non-biodegradable plastic, and until industries start paying for the external damage that their irresponsible waste causes, the AM industry will sadly be business-as-usual in America and environmental problems will not go away.

There are many ways that inventors and scientists have addressed the waste problem within the AM industry. For example, water soluble support materials have been invented and are becoming more popular. “Figure 8: Water Soluble Support Materials” shows a Thingiverse user, Tony Buser, printing a model using polyvinyl alcohol (PVA) as a support material. Once the product finished printing and cooling, Buser placed the product into a glass of water and the PVA

[60] "Great Pacific Garbage Patch." *National Geographic Education.* Web. 9 May 2015.

dissolved leaving only the PLA model.[61] This technique, when perfected, can allow FFF printers not only to reduce their waste and environmental impact, but also will allow FFF printers to create more complicated shapes and parts that are currently difficult or impossible to print with FFF style printers.

Figure 8: Water Soluble Support Materials



Source: Tony Buser

Another way to minimize waste is through cradle-to-cradle recycling, which is something the AM industry currently offers through Recyclebots. Recyclebots convert plastic waste like milk jugs and water bottles into filament for open-source 3D printers. Commercialized examples of these include Filastruder, Filafab, and Filabot. The first recyclebot was developed by University students in Australia. They now are sold through crowdfunding like on Kickstarter. The Recyclebot's plans are freely available on the internet. And this offers great environmental potential for the AM industry. For example, a canoe was built using plastic recycled with milk jugs. Being able to turn household plastic waste into usable filament is an incredible idea, and if

[61]"Fused Filament Printing with Water-Soluble Support - IT Clips." IT Clips RSS. 27 Jan. 2012. Web.

Recyclebots became a commercialized, mainstream resource, the environmental advantages for a Recyclebot would be incredible. Also, according to Dr. Pearce, “Filament is retailing for between $36 and $50 a kilogram and you can produce your own filament for 10 cents a kilogram if you use recycled plastic.” So not only do Recyclebots reduce the landfill plastic waste, but Recyclebots also offer huge economic savings.

Finally, 3D printers digitize the supply chain. Changing the manufacturing model from over-sea transportation, to a decentralized model could make AM a huge win for environmental issues and overall manufacturing carbon footprint. If instead of products being distributed from raw materials to different parts of the supply chain until eventually retailer and eventually customer, the idea of having the chain go straight from raw material to customer could dramatically reduce carbon footprints of 3D printing. Replacing physical inventory with digital inventory is huge, because digital inventory is easier and less environmentally costly to ship. Locally printing and distributing products reduces transportation costs. Digital storage reduces a need for storage, and reduces space used for storing products, which in turn frees up physical land. Finally, cutting the supply chain also cuts the amount of packaging needed for shipping from place to place. All of these factors from minimizing waste, recycling waste in a cradle-to-cradle way, and digitizing the supply chain could make 3D printing a much more sustainable industry than it currently is. However, unless the United States starts making environmental concerns a priority, by putting more funding into the EPA and providing economic incentives to pay attention to environmental externalities, the AM industry will not be the cure to climate change. The United States needs to put climate change and environmental concerns on higher priority than they currently are. Climate change and environmental impact needs to be a national concern instead of a controversial debate. Educated senators need to stop letting the Koch Brothers and lobbyists allow them to indoctrinate American citizens into believing environmental concerns are not a problem. Basically, senators need to stop bringing snowballs into Washington DC and they need to bring funding towards environmental concerns, jobs, regulation, and education if we want to see a serious environmental change for the globe.

Conclusion. The Future of 3D Printing

"Humans distinguished themselves from their evolutionary ancestors by making tools. Additive manufacturing technology may be the ultimate tool that will perhaps change human culture forever."
-Hod Lipson and Melba Kurman

Imagine a future where owning a 3D printer is as ordinary as having internet access or a smart phone. Envision waking up to the smell of breakfast freshly printing, because you synchronized your alarm clock with your food printer. This encourages you to wake up on time, because the food will get cold if you press snooze. Today's breakfast is a spinach quiche with smoked turkey, and you're surprised at how delicious it tastes, considering the recipe came from a diet website. A few months ago, your doctor told you to start watching your weight, so you bought a year's subscription to "Diet Dining" a highly rated healthy printing company. "Diet Dining" is a bit more expensive than other companies, because it is part of the *Get Some Give Some Program*. The *Get Some Give Some Program* has a little over a thousand companies who signed a contract promising for every product bought, the same product will be printed for someone in need. The program is making a positive impact globally, and you are happy to be supporting the cause.

After finishing breakfast, you remember Susan is having a pancreas implant tomorrow. You know she is nervous about it, so you decide to give her a call. Secretly, you think it is senseless for her to be nervous about the implant. Thanks to medical advancements, transplants are much easier now. Organ waiting lists are a thing of the past; tomorrow, her doctors will simply print out a replicated and improved version of her own pancreas. The call went to voicemail, so you go to your closet and look for an outfit to wear. You pick out your favorite dress suit; only to remember that the matching shoes are so worn down they are no longer functional. Since you haven't shopped in a while, you decide to treat yourself, and purchase a new pair of shoes. Several different companies sell nice heels, but you had a specific pair of heels on your wish list for quite some time. After scanning your measurements and the exact color of your suit, the wardrobe printer turns on and starts printing. After fifteen minutes, you are putting on the custom designed shoe. As you head to work, you try to remember how you used to live in a world where sometimes products ran out of your size.

Looking at additive manufacturing in this way, there seems to be no negative effects at all. However, in order for this amount of consumption to be healthy, in order for at home printers to exist, there needs to be more funding in the EPA; there needs to be a significant reduction in electricity use, or solar powered printers need to become commercialized. Because electricity is such a factor in the environmental impact of the additive manufacturing industry, and because globally humans are already consuming too much electricity, there needs to be regulation on greenhouse gas emissions. If the United States makes climate change more of a priority, 3D printing has the potential to be a transformational technology, benefiting its users and the globe. But because currently there are not enough regulations in protecting the environment from negative technological advancements, we could drive ourselves into hyper-materialism, over consumption and a lethal amount of waste. In order to protect the nation from such severities, the government needs to enforce companies and individuals to take responsibility of their ecological footprints. If American companies and individuals continue to ignore environmental externalities, 3D printing will have devastating impacts on the environment. In order to prevent this, the government needs to create economic incentives so that companies and individuals pay attention to environmental externalities. Finally, more research needs to be made on the additive manufacturing industry and its environmental impacts. As we have seen in previous case studies, there are gaps in data and a lot of more research needs to be done to have a complete understanding of the industry's ecological footprint. This research proved that paying attention to environmental risks for the 3D printing industry is essential for the industry to grow in a healthy way. The research also provided a model of how to properly engage in analyzing environmental risks, where more research and findings need to be made, and how policy can prepare if additive manufacturing does indeed become the third industrial revolution.

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