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ROLE OF ADDITIVE MANUFACTURING IN SUPPLY CHAINS TODAY

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ABSTRACT

Additive manufacturing, commonly referred to as 3D printing, is quickly gaining attention in a wide range of industries and markets. From tech enthusiasts, to a generation of "makers," to aerospace engineers, 3D printing provides hope for something revolutionary. While the future holds much potential for tremendous advancements with additive manufacturing, this research will focus on the viable uses of the technology today. It will analyze industries and products, specifically parts, that can benefit from the use of additive printers. Through the identification of common qualities and criteria, the research will help determine the feasibility of using additive manufacturing.

Through extensive research of already existing technologies and successful production of goods, a framework will be created to allow businesses to identify areas that could benefit from additive manufacturing. The research will evaluate the opportunity, benefits, limitations, and needs of additive manufacturing for three main industries: Medical, Military, and Aerospace.

The final framework will provide suggestions for the type of parts that should be produced via additive manufacturing. Parts that could benefit from additive manufacturing will fall under the following characteristics: unique, timely, costly, and high quality.

With the rapid progression of technology today, this thesis will need to be adapted and changed to account for new advancements in the future. The basis of the framework will remain suitable for future analysis; however, the content will need to be updated.

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Chapter 1

Introduction

More than 123,000 people are currently on the waiting list for organ transplants. Unfortunately, every twenty-one minutes someone will die due to the lack of available matches. This can be due to timing, inability to transport organs long distances, and/or an unfit match. But what if one machine could fix this problem, making customized organ transplants close to the point of demand and in a timely manner? Those 123,000 people would no longer be on a waiting list, but rather continuing on with their lives with a perfect match (American Transplant Foundation, 2016). Now imagine a military aircraft needs a replacement part but is far from any source of supply, do they wait for a new part while risking lives and wasting time? If the flight-critical parts could be produced on or near the location of the plane, they could save time and create a safer situation (Goehrke, 2015). Organ transplants and spare parts may seem to have nothing in common but in terms of additive manufacturing technology they may be more similar than we ever thought possible.

The technology for building objects with a machine using a computerized blueprint has been around for over thirty years. As technology advances, however, this idea is changing and becoming more useful in a wide range of industries. Because of its similarities to ink jet printing technology and its ability to create three-dimensional items, these machines became known as "3D printers." This term can be a bit misleading as the machine is not simply printing out a 3D model. The technology consists of using the blueprint to place material one layer at a time and therefore is referred by many as "additive manufacturing." Additive manufacturing comes from its antonym, subtractive manufacturing, which refers to the process of taking material and breaking it down to create the desired model (Savini, 2015). For the purpose of this thesis "3D printing" will be referred to as "additive manufacturing."

While additive manufacturing (AM), by definition, sounds like a simple way to take any digital model and make it into a final product, it isn't quite that simple. Although some see additive manufacturing as the next industrial revolution type advancement, it is still far from reaching this point. AM technologies are being used to produce prototypes, small objects, parts for final products, and other minor aspects of the big picture of supply chain. It is not possible today for large companies to replace production lines with additive printers.

As additive printers are becoming more available and less expensive, the idea that they will revolutionize the supply chain is gaining attention. Companies in a wide range of industries are exploring how they can use additive manufacturing to benefit their company. While there has been significant progress, there are many obstacles that must be overcome to really see a presence of additive manufacturing in companies' supply chains. The main industries that have been exploring this research are: medical, automotive, aerospace and military. The key to this thesis is that although these industries may vary greatly in the products they create, each one is focused on parts- both organic and inorganic.

While additive manufacturing might not be remaking the entire supply chain, it can definitely aid in the production of goods and inventory to revolutionize it in a different way. Instead of focusing on how additive printers can replace the supply chain, this thesis will evaluate its' ability to aid and alter it. The purpose of this thesis is to determine what role the printers have in the supply chain. Specifically, to explore and analyze how they can act as a form of replenishment to aid in the production of parts and organs. While additive manufacturing might never fully take the place of inventory it might be able to aid in the replenishment system. This thesis will develop a framework that will allow companies to identify the need they have and whether or not it is worth making it through additive printing or through traditional manufacturing.

Spare parts for a Boeing 787 and bioengineered organ transplants can both be created using additive manufacturing (CSC, 2012). The concept that a single technology, using different materials, can create such different items is one of the key points in this thesis. Through research of additive manufacturing in the present, rather than the future, this thesis will create a framework for what “parts” can and should be manufactured using this technology. Instead of looking into the future of additive manufacturing and how it might one day be able to revolutionize supply chains across the globe, this research will look at the present day and how it can be used now to advance supply chains. The thesis will begin by explaining the history of additive manufacturing and an explanation of how it works. Three different industries will be analyzed to identify current needs, opportunities, and issues with additive manufacturing utilization. The industries being analyzed are medical, military, and aerospace. This analysis will ultimately lead to the framework that can be used to identify when a company should choose to use additive manufacturing as opposed to traditional manufacturing.

Additive Manufacturing Decision Framework

The framework will encompass the main criteria needed to successfully utilize additive manufacturing. These criteria include: timing, uniqueness, quality and limitations (cost and materials). This way companies in all industries can use the same set of qualifications to determine the feasibility of producing any product. The idea that working in silos can hinder progress can be seen often in technology as sharing of information is often limited due to competition. However, if companies across contrasting industries can share information about AM developments using a similar language, greater strides can be made towards successful additive manufacturing.

Time will be a key part of the final framework used to determine whether or not AM should be used. While the technology is advanced and can make products in one machine that otherwise would have needed to be made through a complex supply chain with multiple production steps and large complicated transportation networks, the additive printer may not have the speed and efficiency needed to keep up with demand. If production time using AM is longer than traditional production, AM may not be the best choice for that particular product. However, if it takes less time to produce a key part using AM and can be done closer to the point of demand, the framework could then be used to determine if the rest of the criteria comply. Additive manufacturing may be able to be used to reduce lead time.

Another criterion in the framework is uniqueness. A major benefit of additive manufacturing is its ability to create more unique products than traditional manufacturing. Organ transplants are a good example of a unique model that would benefit from being made using AM technology. If an organ can be made from data from a specific patient using their own cells to create the end product, they are much more likely to have a successful transplant. Parts used in other industries that are very complex and take multiple components to create also present an opportunity with AM to simplify and increase success of that product. This can all be done with a simple change of computerized blueprints as opposed to transforming entire production lines to adapt to unique products.

Cost of production will also play a major role in deciding whether or not a part should be made using additive manufacturing. The importance of the other criterion will alter whether or not cost is a key component in the decision making process. For the military, cost is less important than getting high quality products, to the right place, at the right time. On the other hand, a company that mass produces standard parts for a very low cost may not be willing to make the switch to additive manufacturing.

While there is a wide rage of materials that can be used in additive printers today, there are some that have not been adapted to this type of manufacturing which could limit what products can be made. For all industries quality is extremely important, therefore the material has to be durable and must be tested before integrated into a final product.

Intellectual Property and Ethical Issues

With advanced technology comes faster and easier spread of information and ideas. Since additive manufacturing uses digital data to create its products, there is an increased risk to the sharing of patented blueprints.

This thesis will also look at the ethical and legal issues that come along with additive printing. Who owns the rights to product blueprints? Will companies sell their blueprints to a 3rd party or own their own printer? What patent and licensing issues will come with the reduction of cost and increased availability of additive printers? How far can organ creation go before it is considered unethical?

Chapter 2

Background

History

In 1984, Charles Hull invented Stereolitography (STL), which creates 3D models based on digital designs. The model is created by using a UV laser light to harden liquid polymers layer by layer. At the time of this invention it was seen as a great tool for inventors in order to prototype their designs at lower costs than manufacturing them (Goldberg, 2014). Additive manufacturing takes the concept of taking a block and getting rid of useless material to make a product, and reverses it. Instead of breaking down material, additive printers build layer by layer based on slices of a digital design (Savini, 2015). By the late 1980's another form of additive manufacturing was created at the University of Texas, called Selective Laser Sintering (SLS). SLS uses a laser to melt down powder particles as opposed to the STL technology which utilized liquid material. Another technology developed in the 1980's was Fused Deposition Modeling (FDM) which deposited thermoplastic material in layers using a 3-axis robot.

Advancements and adaptations to additive manufacturing technology continued to occur and in 1999 a huge step was made when the first printed organ was implanted into a human. At the Wake Forest Institute for Regenerative Medicine, synthetic scaffolds of the human bladder were created and then covered with patients' cells. They successfully implanted these printed bladders into actual patients, knowing that the probability of rejection was low since the cells used were those of the patients, meaning they matched perfectly (Goldberg, 2014).

Until the early 2000s additive printers were very expensive (millions of dollars) and were mainly used for prototyping in large industries. The goal then became to make lower cost printers that could be acquired by individuals. Additive printers have become so affordable today (as low as $300) that even individuals can buy their own personal AM printer. The move toward making more affordable additive manufacturing technology encouraged more at-home additive printers which added to the amount of DIYers and tech enthusiasts (Savini, 2015). The cost reduction has definitely helped to increase the awareness of additive manufacturing and also has allowed technology to advance more quickly as open source concepts encourage people to share ideas, blueprints, and breakthroughs in technology (Lopez, 2014). Most of this has been seen to effect the at-home printers, however, at-home printers will not be the focus of this thesis. Commercial use of additive manufacturing for production of parts takes more advanced concepts that are still being researched which is why this thesis focuses on today's applications.

In 2005 the first self-replicating printer was created, meaning the printer was able to print all parts necessary to create another working additive printer. By 2015 the following had been developed: functional kidneys, prosthetic legs, unmanned aircraft that took flight, printed car body, food printing and much more. It is clear that there has been a very wide range and large amount of fast-paced advancements in additive manufacturing (Savini, 2015).

A recent advancement in additive printers by Carbon3D is called the Continuous Liquid Interface Production technology (CLIP), which is being called the "modern" 3D printer as if to say the others on the market are old-fashioned. All other printers on the market deposit thin layers of only 50 to 100 microns thick which means it can take hours to print something that is only centimeters tall and contains some ridges from the separate layers. The CLIP technology is quite different. The machine uses a pool of resin that hardens with UV light but stays as a liquid when exposed to oxygen. The light is used to make the pattern of whatever design the computer tells it to create that way the parts exposed to the light harden into the desired shape. The machine works simultaneously to rise up and pull the object out of the resin pool as it is being formed. This means the creation of an object is more continuous than the usual layer-by-layer production. What this machine can produce in 6.5 minutes would take 3 hours on most other additive printers in the market. Not only is the technology 25-100 times faster it also creates smoother, more intricate objects, including medical devices and operating parts. The CLIP technology can be seen in Figure 1 below (Engelking, 2015).

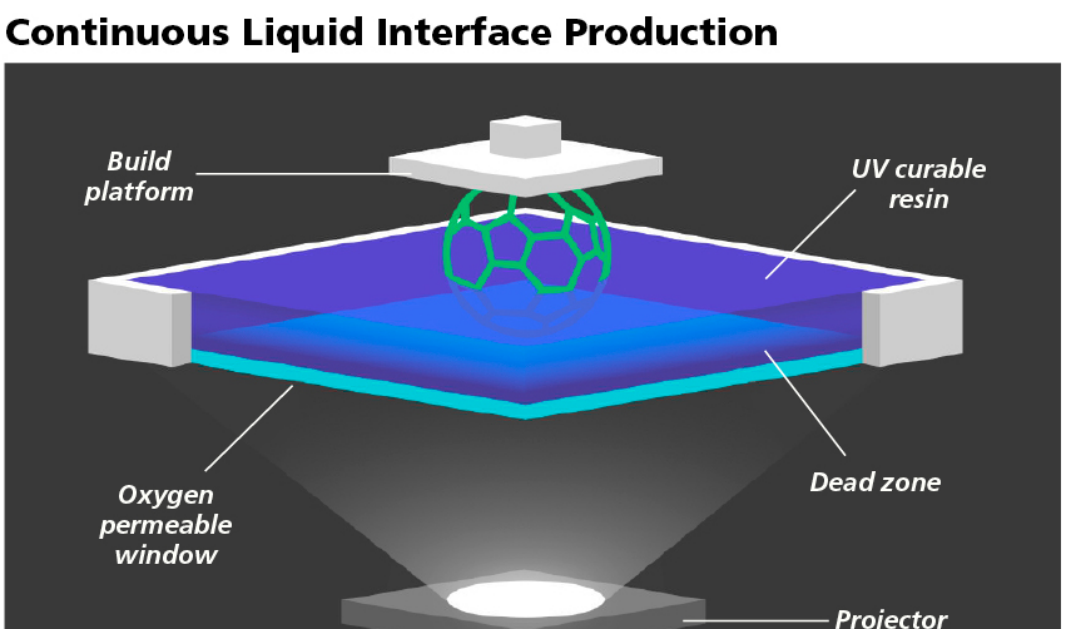


Figure 1: CLIP Technology

The areas utilizing additive manufacturing today include aviation and automotive industries that use metals and plastics to produce parts and mechanical tools, electronic industries printing circuit boards, medical fields producing prosthetics and tissues, and even fashion and food industries exploring new creative ways of production. Technology is growing so quickly making boundaries for design disappear, but can people think outside the box enough to utilize these technologies to the best of their advantage?

How It Works

In order to create an object using an additive printer a blueprint must be uploaded to the machine. There are two ways to do this: create a CAD (computer aided design) file using a 3D printing program, or scan an object with a 3D scanner that will be placed into a modeling program. Once a blueprint is created it can be sliced into layers and used in any 3D printer through coding sent to the printer. Usually material is placed down in about 16 micron to 100-micron layers. Materials that are currently being used include: photopolymers, wax, aluminum, thermoplastics, paper, nickel, titanium, ceramics, epoxy resins, chocolate, and more. Many materials are still being developed and tested. The amount of time the process takes depends on the shape, size, and desired quality of the object.

Depending on the type of printer, liquid or powder are placed down to build the platform and then the subsequent layers follow. With a powder based machine, such as the Selective Laser Sintering (SLS) machine, powder is placed down and then fused in certain points that are determined by the blueprint in order to create the layers. With liquid based printers, like the

Sterolithography printer (STL), it is a similar process except the liquid is hardened by the laser. CLIP technology differs from both of these methods and was explained above.

Producers

The U.S. still leads additive printer production, with Japan, China, Israel, and some European countries trailing behind. Companies range in focus and technology and can offer different services to different markets. For the purpose of this research the focus will be on companies that have a focus on commercial production past prototypes and that serve the automotive, aerospace, military, and medical industries.

3D Systems

3D Systems provides advanced designs and solutions for many industries. They offer on demand printing of parts, full design to print solutions, and even training and planning support. Materials such as plastics, elastomers, metals, and bio-compatible materials can be used using their technologies. 3D Systems technologies include SLA and SLS printers, Colorjet Printing (CJP), Multijet Printing, Virtual Surgical Simulation (VSSTM) for 3D health care products, and Geomagic Design X (XOR) software (3DSystems.com).

Carbon3D

Carbon 3D was founded in 2013 in Chapel Hill, NC but is based in Silicon Valley. They focus on providing commercial customers technology to manufacture rather than just prototype. The CLIP technology was invented by Carbon3D and is being used across all industries to create very complex products in a shorter amount of time (AMUG, 2016). The main idea behind the CLIP technology and Carbon3D as a whole, is to grow products rather than produce them layer-by-layer in order to ensure quality and speed that can actually transform manufacturing.

Concept Laser

Concept Laser Inc. is now located in Texas but was originally established in Germany in 2000. They specialize in additive manufacturing with metal materials, making them advanced in aerospace, automotive and medical industries when metal is involved. Concept Lasers use powder based machines to produce many types of metal parts with capabilities for high- grade steels, hot work steels, stainless hot-work steels, aluminum alloys, titanium alloys, nickel-based alloys, cobalt-chromium alloys, bronze alloys, and precious metal alloys (Concept Laser Inc., 2016).

EOS

EOS, E-Manufacturing Solutions provide software, materials, systems, and consulting for additive printing technologies. They provide long term solutions to customers by focusing on light weight structures, lower cost, complete customization and faster development-to-production processes (AMUG, 2016). Their focus is to "enable a design-driven manufacturing process- where design determines production and not the other way around." EOS has developed a Micro Laser-Sintering Technology which allows very small, highly individualized, complex parts that need to be light-weight and extremely durable, to be produced. This technology may be useful for medical technology, electronics, and other industries with a need to these specific parts (EOS, 2016).

Organovo

Organovo is a leader in the bio-printing of human parts for research, testing, and functional implants. Their goal is to bridge the gap in the medical field and to provide advancements that will help improve drug and medical practice development. Whether that means removing risk from drug testing by allowing companies to test on printed organs rather than real ones, or increasing the supply of implants that can save the lives of many people waiting for a match. To create the printed tissue, Organovo starts with a design that the bioprinter uses to generate the tissue, then “bio-ink” is dispensed in layers to create the desired design. Bio-inert hydrogel can be used to support the design in any way that is needed to create the final object.

Strengths of Additive Manufacturing

The greatest opportunity generated by additive manufacturing is the idea that it can create solutions for products that otherwise may have limitations (complexity, miniscule size, detail, material, components). It creates boundary-less manufacturing. The only thing that can hold back the creation of a design is the ability to think that creatively and critically, whereas a typical manufacturing process may limit design capabilities (EOS, 2016). Additive manufacturing also allows models to be lighter and potentially more stable with the elimination of multiple parts and the creation of one unison piece. The technology allows for wide range of customization with a simple change of blueprint rather than traditional manufacturing that can be very expensive to customize at all.

Another benefit of additive manufacturing in comparison to traditional manufacturing is the opportunity for waste reduction. Additive manufacturing provides an opportunity to reduce excess raw material usage and allows for less energy consumption than a traditional production line. Also, with AM being “on-demand,” less resources will be needed to fulfill demand and transport finished products (Huang, 2012). Along with great benefits, additive manufacruting also presents limitations as the technology continues to be developed and adapted to overcome obstacles and fit products of all types.

Limitations of Additive Manufacturing

There are many limitations that come with additive manufacturing. With the technology being only about thirty-years old there are still advancements that need to be made before some products can be produced and function properly. New materials are being discovered but not all have been made durable enough to be sustainable. Other obstacles that need to be addressed are costs of materials, quality of finished product, as well as, size and capacity limitations (CSC, 2012). These obstacles can be overcome as advances in technology are made, and there have already been great strides to make additive manufacturing more of a reality than a dream. However, an issue that may be more difficult to overcome is the legal and ethical issues that could inhibit future growth and spread of AM technology.

Ethical and Legal Issues

As additive printers become more affordable and more widely available, issues are beginning to arise with the law. Individuals and companies have the ability to produce a wide range of products using a simple blueprint, which leads to issues with copyright, patents, and trademarks. The same issues occurred when home computer and printers became prevalent due to the ease of sharing and reproducing information. However, issues specifically related to additive manufacturing still need to be addressed and regulations will need to be created. If people can produce anything in their household with an additive printer, there would be no incentive to buy and trademarks, patents, and copyrights would easily be violated. As stated before, all objects made on an additive printer begin as a CAD file on the computer that is a blueprint of a virtual object. The CAD file can be manipulated as the designer wishes without having to physically build or prototype the object. Since it is a computer file, the blueprint can be easily and quickly distributed (Weinberg, 2010).

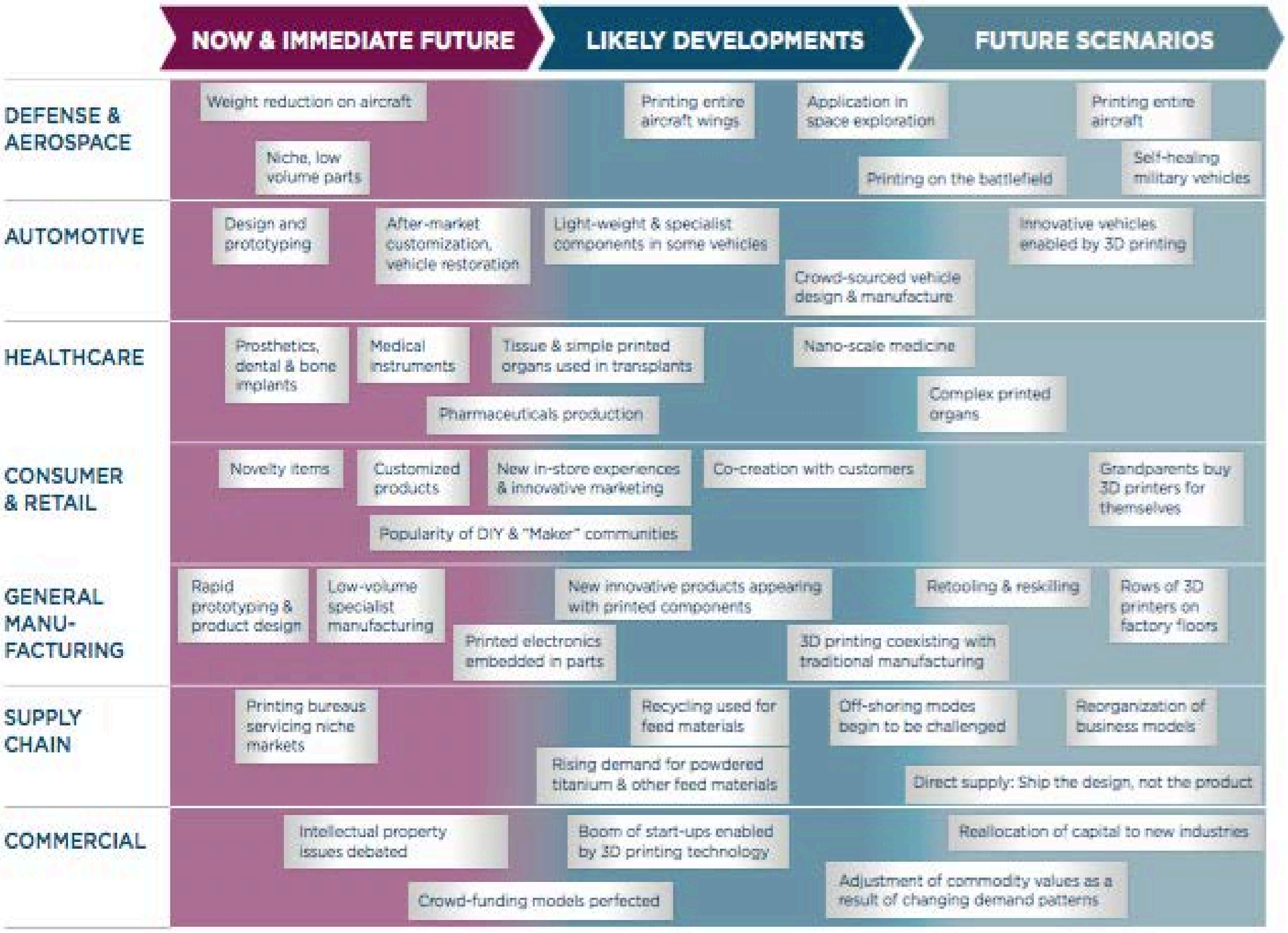
New issues arise with additive printers as there is a thin line between the creative blueprint and the physical model. Copyright generally protects creative, written material, not physical and functional products. Products are instead protected by patents, which stop others from reproducing the same invention. Patents only last a short amount of time and take time to acquire. Additive manufacturing falls in between both patent issues and copyright issues, depending on the portion of the process being discussed, as well as trademark issues when dealing with commercial products (Weinberg, 2010). This makes protecting additive manufactured goods very hard to accomplish. Issues that need to be addressed are s follows: who owns the blueprint, how can blueprints be shared, and how are blueprints and final products protected?

It is important to note that since actual laws specific to AM technology does not exist yet, companies need to be prepared to either do their best to follow copyright and patent laws or be able to fight for their rights in court. Manufacturers must be able to work with Congress to establish flexible rights to protect blueprints and printed products in order to ensure that additive manufacturing can continue to grow and improve without expensive litigation that could limit the future of this technology (Swanson, 2014).

Future of Additive Manufacturing

The research done for this thesis was meant to be for the present day uses of additive manufacturing. However, with technology changing rapidly and the reality that the technology available has far exceeded the possible commercial uses available, we can speculate what the future of additive manufacturing may look like. It is important to note that the framework produced by this thesis will likely need to change each year with the addition of new advancements.

The future of additive manufacturing can be predicted by making assumptions about how technology will advance. It will be assumed that eventually material costs will be reduced and the amount of materials able to be used will greatly increase, also the speed of manufacturing will increase and the size and capacity limitations will be mitigated. As shown in Figure 2, it is expected that eventually entire aircraft and vehicles will be produced using additive manufacturing. Organs and on-demand medical needs will be printed for both point-of-need organ transplants and battlefield support. Manufacturing may even be revolutionized by additive machines and could one day replace production lines as we know today. Although these advances are far from a reality, changes are being made everyday to the technology making us one step closer to this (CSC, 2012).



Source: CSC

Figure 2. CSC 3D Printing Impacts

Chapter 3

Analysis

As the majority of this research comes from literature, the literature review will be incorporated into the analysis section and will be used to aid in the evaluation of each topic. The analysis section will explore the use of additive manufacturing of “spare parts” for the following industries: medical, military, and aerospace. Each industry was assessed to identify current issues and to find where there is a need or opportunity for additive manufacturing. Extensive research allowed for a broad analysis of the industries and also provided specific examples of current developments. The criteria used to analyze each industry include current issues within the industry, opportunities for additive manufacturing to mitigate those issues, timing, materials needed, costs, and limitations. Research was done through a variety of outlets in order to gather information about all industries in a way that could then be compared uniformly using the same criteria. The analysis section provides context and reasoning for the final framework in this thesis.

Medical

Current Issues

One major issue in the medical industry is the shortage of organ transplants. According to the United States Department of Health & Human Service, there is a widening gap between the number of transplants needed and the number of available donors. Many people need organ transplants due to disease, accidents, and other complications. Organ transplant patients often have to wait a long time to get an organ. The organ must be a match in order to avoid rejection, which occurs when the immune system attacks the new organ. In order to determine if an organ is a match many things are considered including urgency and need, the amount of time the patient has been on a waiting list, size of organ, blood type, and genetic makeup. There is a list called the “OPTN National Transplant Waiting List” that patients are placed on once they receive a referral from their physician. A big part in determining if an organ can be donated is the amount of time that organ can be outside the body and still function. This can be greatly affected by the amount of distance between the donor and the recipient due to the amount of time transportation takes (U.S Department of Health and Human Services).

Another issue in the medical field falls within orthopedics. Often standard prosthetics and implants are insufficient as every patient’s situation and biological makeup differs. In these cases, surgeons need to add bone graft, or perform surgeries that involve drilling and sculpting to change the standard model to fit the patient. This adds time and complexity to the implantation or prosthetic creation (Ventola, 2014). Prosthetic limbs are often very expensive and standard versions may not allow the patient to be fully functional (McCue, 2014).

These issues can be resolved or improved with the use of additive manufacturing. The use of AM technology in the medical field will be evaluated below, followed by the limitations that are still present.

Need and Opportunity

Organs that can be transplanted include the heart, intestine, kidney, liver, lung, and pancreas. However, there is a much higher need than there is availability of these organs.

Printing organs through additive manufacturing technologies could allow much more than just more organ availability. If organs could be printed on demand it would eliminate the need to transport the organ long distances, therefore reducing the amount of time the organ would be outside a body. Additive manufacturing of organs would also mitigate the risk of a patient’s body rejecting an implant. Finding a perfect match is very difficult and inserting a human organ into another body runs the risk of rejection due to the fact that the patient’s body does not recognize the new organ. If technology allows it, organs that fit the need and genetic makeup of the patient would be much more personalized than a donor organ. The organ would be made of the patient’s own cells, greatly reducing risk of rejection. The organ would be designed using actual images of the patient’s body which would be converted into a CAD file to then be printed in layers.

While bio-printing a wide range of fully functioning human organs may need years or decades to really become successful, the current technology can be utilized in many other ways today. Custom prosthetics, small strips of organs or tissue, skin, facial and cranial implants, can all be produced today to help in recovery and/or research. Printed organ and tissue strips can be used to test new medicines and vaccines. Even more unique to additive printers, tissue samples from an individual patient can be printed onto chips and used to test specific treatments (Griggs, 2014). Organovo has been printing strips of human liver for drug testing and has also teamed with L’Oreal to print skin tissue in order for them to test their products before they enter the market (Organovo, 2016). Other successes in this industry include bio-printed blood vessels, vascular networks, bones, cartilage, ears, tracheal grafts, custom skull components, and even successful bladder implants (Munoz-Abraham, 2016).

Another large opportunity is within orthopedics. Additive printers have the ability to create custom prosthetics and implants (including dental, hip, and spinal implants) for patients that need more complex or customized versions than the standard one. A major benefit of this is that the additive printer can take an image from an MRI or CT scan and print a customized implant or prosthetic that will fit perfectly into the patient. Hearing aids are an example of this benefit as everyone's ear canals are different and therefore need a different shaped hearing aid to be most effective. Additive printers can completely customize the hearing device to each patient using the blueprint that was created from their specific ear canal. The use of the additive manufacturing allows for this customization to be done more easily and cost effectively than if it was made through mass production. Today, almost one-hundred percent of hearing aids are made with AM technology. Other benefits of using AM technology for surgical implants and prosthetics include reduced time of production and cost effectiveness, both of which will be discussed below.

Timing

In order to print an organ, a blueprint of its vascular makeup is needed and a bio-printing process plan must be put in place. Next, stem cells must be isolated and differentiated into organ-specific cells. The bio-ink and other cell materials must then be loaded into the printer. Once the organ is formed it needs to be placed into a bioreactor before it can be transplanted (Ventola, 2014).

It takes Organovo forty-five minutes to produce small strips of liver tissue and two days for cells to grow and mature. These strips can then survive for forty days. The forty-five minutes it takes to print each strip is just a small portion of the organ, not the whole organ itself. However, when compared to the average amount of time a patient will wait for a transplant from another human donor, the opportunity for AM technologies to greatly reduce the time to transplant is evident.

According to the Gift of Life Donor Program, depending on the organ, the average median wait time for transplants can range from four months to five years. The wait time is determined by the need and urgency of the transplant as well as the inevitable need to wait for a perfect match. The wait time is widely varied as a result of differing patient needs and availability.

Prosthetic limbs and custom implants can be made within twenty-four hours, which is much faster than the usual implant process. Typically, implants have to go through a validation process after production which adds to the total lead time (Ventola, 2014). This time could be lessened if the implant or prosthetic was already made and tested for a specific patient.

Materials

The materials needed for bio-printing organs include: organ-specific cells, blood vessel cells, support medium, and bio-ink reservoirs (Ventola, 2014). For prosthetics and surgical implants metals and plastics are used depending on the type and size needed.

The biology behind the body and how each organ works together clearly affects what parts can be made and how they can be successfully utilized. While biological material is available and has been successful, there are many factors that inhibit further advancements of bio-engineering.

Costs

Additive manufacturing technologies may reduce costs in the medical field by reducing transportation and/or material costs, however investments are still needed to achieve these savings. In the case of saving a life, costs may be less critical than speed or effectiveness. Therefore, an increase in costs to additively manufacture an organic part in the medical field may not be a reason to use traditional methods.

Some cost savings are prevalent in the case of prosthetics. A prosthetic hand would cost $50 on the additive printer used by e-NABLE as opposed to the commercially made model which costs $30,000-$50,000 (McCue, 2014). This difference provides patients with custom-made, high quality solutions without the typical high costs.

Limitations

Bio-engineering organs and other components of the body causes both legal and ethical concerns. Parts being produced to match a patient's body could potentially save many lives. However, if there is no limit to who can access this technology and what can be produced, bio-printing could be abused. Legal rights must be put in place to regulate this issue, although regulations may limit the positive research and development at the same time.

Military

Current issues

U.S. Military ships, aircraft, vehicles and equipment must be reliable, durable, and safe in order to ensure a long lifespan and the ability to withstand extreme environments. If a component part needs to be fixed it must be done immediately and possibly in remote areas. Therefore, a large amount of inventory is needed on ships, aircraft, and military bases in order to ensure that at any time, if a component breaks or malfunctions, there will be a replacement part on hand. This inventory takes up space and weight that could otherwise be used in a more productive way.

Another issue that the military faces is a result of discontinued or obsolete parts. While a part may be critical to the military, a manufacturer may choose to stop production and offer lifetime buys. Lifetime buys consist of buying all the inventory of a specific part or product in order to have enough to fulfill future demand even when production stops. This type of buying is very risky as future demand may be difficult to predict and large amounts of inventory adds expenses. Third party logistics companies are often used by the military to hold large amounts of inventory in storage. This 3PL company must be experts in storing, monitoring, and transporting these goods as the inventory and distribution system is very complex (Leno, 2015).

Lastly, like many companies, the military's supply chain professionals are constantly trying to evaluate ways to reduce lead time and backorders and increase flexibility. These logistical issues are amplified in the military as the parts and products flowing through the supply chain are crucial to the lives and success of military personnel. Finding ways to mitigate these issues is critical (Leno,2015). The military's supply chain can be extremely costly as finding alternatives or delivering late is not an option; expediting is a must and cost is not of the highest concern when it comes to safety and necessity.

Need and Opportunity

Additive manufacturing presents the military with the opportunity to reduce costs, increase supply chain flexibility, allow for product customization, and allow production to occur closer to the point of need (Louis, 2014). There is also an opportunity to reduce the weight of parts and greatly reduce inventory. If replacement parts could be printed on board an aircraft, a ship, and at naval bases, many supply chain barriers would be diminished. This would eliminate excess inventory and allow for point of demand production. Deployed troops would have the ability to keep up with maintenance and operations on their own. This would allow for product customization while reducing labor, production, and transportation costs (Harper, 2015). According to the U.S. Army Logistics Innovation Agency, additive manufacturing could reduce wait time by 3-153 days (Leno, 2015).

As discussed above, the military faces issues with obsolete parts due to the long lifetime of many of the ships, aircraft, and equipment. For example, the B-52 aircraft was first created in 1952 and not only is it still used today, but also there are plans to use it until 2044. As a result of its age, many of the components that make up this aircraft are now obsolete. Additive manufacturing can be used to construct replacement parts on demand at the location of the aircraft, eliminating the need for lifetime buys, large amounts of inventory, and additional storage space (Louis, 2014).

Additive manufacturing would reduce the need for large manufacturing sites and 3PL warehouses that hold excess amounts of inventory. This would lessen the complexity of the supply chain as a whole and save costs. In the future, Navair hopes to be able to produce ammunition and also take advantage of bio-printing in order to aid injured personnel (Goehrke, 2015). The opportunities are vast for the military as many of the criteria this thesis finds necessary for additive manufacturing are satisfied.

Materials

Currently Navair uses plastics and polymer components and hopes to further develop metal 3D printing. Some metal materials have been affected by the printing process causing improper cooling (Goehrke, 2015). If additive manufacturing processes cause parts to have malfunctions and are not reliable or of the highest quality, they cannot be considered for use in military vehicles or equipment. Military equipment must be strong, durable, and reliable.

Limitation

A limitation to the advancement of additive manufacturing in the military, is the threat to cyber security. The chance for cyber warfare puts the military at risk of leaking designs and blueprints to enemies (Louis, 2014). There are concerns that CAD files being sent to deployed troops to produce could be manipulated by an enemy to create malfunctions in aircraft and equipment (Harper, 2015). Along with cyber security comes intellectual property rights. Many of the products used by the military are acquired by external sources and therefore would require licensing rights in order to recreate them with additive manufacturing (Louis, 2014).

In order to fully integrate additive manufacturing into the military, training and development is necessary. Deployed military personnel will need to be trained in creating CAD files and operating the machinery to ensure quality. If additive printers were to be used at point of demand, there would need to be facilities that could accommodate the needs of the technology, including climate controlled rooms and proper power sources (Leno, 2015).

Cost

According to the U.S. Army Logistics Innovation Agency, AM may still cost 3-28 times more than traditional manufacturing (Leno, 2015). For the military however, lowering costs is not considered as essential as getting the highest quality equipment to the right place in the least amount of time.

Timing

A short lead time is essential when it comes to getting a replacement part or piece of equipment to the military base or point-of-need. If a part could be printed at the point-of-demand, there would be a clear reduction in lead time. As stated above, additive manufacturing has the potential to reduce wait time by 3-153 days (Leno, 2015). However, if additive manufacturing is only able to be done at a specific facility, traditional manufacturing may end up being the more efficient option.

Aerospace

Current issues

A Boeing 737 consists of 367,000 parts, which are made all across the world and then shipped to one location to be assembled. Each part adds weight and complexity to the aircraft. The key issues that manufacturers constantly struggle with are excess waste, too many parts, excess inventory, and timing. The more weight on a plane the higher the fuel costs. According to

American Airlines, reducing the weight on an aircraft by one pound can save over eleven-thousand gallons of fuel per year (CSC, 2012). Parts coming from overseas can take weeks to get to the assembly facility causing timing issues, along with production down time. The time it takes to design a new part and get it to production also adds a delay to the process.

Aerospace components must be of the highest quality and be able to withstand extreme environments, such as high heats running through parts, which must have a long lifetime and guarantee safety and efficiency.

Need and Opportunity

The major opportunities provided by additive manufacturing for aerospace are cost-effectiveness, reduced weight and waste, reduced complexity, and more efficient timing (EOS, 2016). As weight reduction is a key goal, there is an opportunity for additive manufacturing to replace current manufacturing practices. Additive manufacturing can produce parts with complex designs, like hollow or honeycomb structures which reduce weight without compromising strength. Since less material is used to make these complex components, not only will weight be reduced, but also cost will decrease (Wong, 2012). Lightweight parts allow for reduced fuel consumption which also adds to cost savings. Components of GE's aircraft that were once fifteen or more components can now be made in one piece using additive manufacturing. This means no welding or other additional processes are necessary as the component is printed as a whole. Additive manufacturing could be used to improve the performance of the aircraft, reduce the amount of maintenance required, and consolidate parts.

GE has had success with additive manufacturing and already utilizes printed parts on fully operational aircraft. Currently they are working to produce fuel nozzles using AM technology. The fuel nozzle sprays fuel into the combustor at temperatures that exceed 3000 degrees. As a result, carbon deposits form over time on the nozzle making it less efficient. To solve this problem, additive printing was used to create a new fuel nozzle design. The printed nozzle is five times more durable and instead of being made of eighteen parts, it is printed in one unison shape. This makes it twenty-five times lighter. With nineteen fuel nozzles in every engine, the weight reduction is significant. By 2020, GE plans on printing over 100,000 parts for their aircraft and are working to develop more powerful lasers to make the process more efficient and effective (GE Aviation, 2013).

Boeing has also been able to utilize additive manufacturing to achieve the benefits described above. In 2012, they had already printed 22,000 parts that functioned successfully in their aircraft. Like GE, they had a part which originally was made up of twenty components by traditional manufacturing. They were able to redesign the part and produce it through additive manufacturing in one piece. This part is called Environmental Control Ducting (ECD) and is used in the Boeing 787 aircraft. Printing this part eliminated the need for an assembly production line, reduced inventory needs, and allowed for less maintenance (CSC, 2012).

Timing

Lead time for aerospace components could be greatly reduced with the use of on-site additive manufacturing, as parts are currently being shipped from all over the world and can take weeks to arrive at the manufacturing site. Delays in transportation add to down time when assembling all the parts of an aircraft, making timing very important. Another time saving component of additive manufacturing is the design-to-production period. When a part is re-designed or a new part is introduced, the supply chain must be adapted to account for the changes which can take time and effort. However, additive manufacturing allows engineers to design and create new parts themselves which reduces the complexity and overall time of the process.

Materials

GE uses a Direct Metal Laser Melting machine which fuses metal powder together into layers until the part is grown (GE Aviation, 2015). The machine uses a two-hundred-watt laser to lay the powdered metal down. Other metals and plastics can be used as well, however the most common material is powdered metal.

Costs

Although the initial investment in AM technologies may be significant, additive manufacturing companies argue that the technology will actually save costs. For the creation of aerospace components on an additive printer, there is no set up cost and the production cost comes mainly from raw material acquisition. New product design can also be cheaper as the design simply requires a computer file rather than a new production line (EOS, 2016). GE planned to invest three and a half million dollars into new AM equipment within five years as of 2010, but as discussed above, the result was cost reduction from reduced weight and decreased complexity (GE Aviation, 2010).

Limitations

One limitation that affects all industries is the concept that what you put in is what you get out. A CAD file needs to be able to be created in order to print the final product meaning the limitation lies within the engineers' ability to develop the idea and design. Additive printers are often more flexible than traditional manufacturing, but the nearly limitless boundaries require a new way of designing and thinking.

With aerospace in particular, quality is of the utmost importance. All parts need to be tested for their ability to distribute heat and to ensure no degradation occurs. Also, parts must be able to be reproduced to the same dimensions and quality every time (EOS, 2016). With such specific qualities and standards that each part must meet, printing components of an aircraft can be more timely and complex than there is time and money for. A cost benefit analysis could be performed to determine the practicality of using additive manufacturing.

Chapter 4

Framework

This framework (Appendix A) evaluates the conditions that differentiates additive manufacturing from traditional manufacturing. Each box in the framework explains the key aspects of a product that determine which type of manufacturing is most suitable. The criteria are on the left side of the table and are broken down into two sections, additive manufacturing and traditional manufacturing. The analysis section provided the background as to why these scenarios allow for better and more efficient processes. It should be noted that there are no specific industries or products in the framework table as the point of the framework was to be applicable to a wide range of parts. Therefore, organic parts can be evaluated using the same table that inorganic parts use.

The framework has four criteria that determine if a part would benefit more from additive or traditional manufacturing. The four criteria are uniqueness, timeliness, cost, and quality. In the analysis section there were more detailed criteria discussed, however to simplify the framework they were all placed within these four categories. Uniqueness includes custom parts, size specifications, and obsolescence. Timeliness incorporates aspects of lead time, production time, and location of manufacturing in respect to demand. Costs refer to expenses at each stage of the supply chain, including design/prototyping, production, transportation, and storage. Lastly, the quality criteria incorporates both material restrictions and weight requirements.

The framework can be used as a basis for decision-making. It is a starting point to determine the most suitable type of manufacturing needed to create a specific part. It can show where in the supply chain additive manufacturing will be able to play a role and where it may not be worth it. This is based on qualitative information rather than quantitative data. A company looking to produce a specific part could perform a cost-benefit analysis to determine whether or not the outcome of integrating additive manufacturing into the supply chain can outweigh the cost of the initial investment.

Chapter 5

Concluding Remarks

Additive manufacturing technology has been around for almost thirty years, yet throughout that time it has changed rapidly. This thesis topic was developed about one year ago and in that time the number and volume of advancements increased constantly. As companies are investing in research and development for additive manufacturing more and more progress is being made. Because of this rapid change in technology, the details of this thesis may become outdated. The basis, however, that all industries can be evaluated under the same criteria to determine the feasibility of additive manufacturing, will not become obsolete.

While the framework can be used to guide the decision making process for additive manufacturing versus traditional manufacturing, a cost benefit analysis could add an additional level of evaluation to get a better idea of the effects of each decision. Moving to additive manufacturing can require a large initial investment, as any new R&D move would require. This investment should be compared to the potential cost savings from switching to additive manufacturing.

One difficult part of writing this thesis was avoiding the mindset that additive manufacturing is the solution to everything and that it will soon be able to make anything, anywhere. It was common in this research to see future predictions for what additive manufacturing will provide, however there are many adaptations and progressions to be made before all of this is possible. The purpose of this thesis was to analyze what additive manufacturing could provide industries with today, not in the future. Only time will allow us to see progression; predictions are simply an educated guess based on assumptions.

Conclusion

While this thesis does not provide an actual analysis of the future, it shows the potential for the future of additive manufacturing and the clear benefits it already provides. In just thirty years, additive manufacturing has moved from simple prototyping to bio-printing successful organ components. Flight-critical parts are being printed and successfully utilized in aircraft. With this progress comes the desire to revolutionize even more parts and products and continue to enhance the existing technology.

Additive manufacturing clearly provides the opportunity to create more unique and higher quality parts at a more efficient rate than traditional manufacturing if used to its full potential. It may not be revolutionizing entire supply chains yet, but it is definitely revolutionizing certain parts of the production process. If using additive manufacturing can reduce weight of a product by twenty-five times, or decrease wait time by nearly 100 days, then there is clearly something revolutionary happening. The aspect that makes it so revolutionary is the ability to be utilized for one specific part, then changed to be utilized for a completely different part, while being located close to demand, in a very short amount of time. The software allows the quick changes in designs, and the availability of the machines allows for point-of-demand production. In conclusion, additive manufacturing can help to create greater efficiencies today and shows potential for the future.

Appendix A

Framework for Additive vs. Traditional Manufacturing

Criteria	Additive Manufacturing	Traditional Manufacturing
Unique	- Customized parts - Complex design (i.e. honeycomb or hollow) -Miniscule size or detail work -Part is obsolete	-Mass production with no customization -Uniform parts with automated production line
Timely	-Parts needed at point-of-demand -Printed faster than prior lead time -Components produced by one printer rather than various locations and combined -Elimination/reduction of transportation is essential	-Parts that can be expedited; cost is irrelevant -Lead time is insignificant
Costly	-New design that lacks economies of scale -Custom parts to be more economical -Parts with high transport cost -Need for reduction in inventory	-Mass production for economies of scale -Efficient process due to repetition
Quality	-Higher quality material available -One durable part rather than multiple components -Cheaper/faster prototype -Weight reduction needed	-Materials unavailable to AM -Lower costs of raw materials

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ACADEMIC VITA

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Education

The Pennsylvania State University, Schreyer Honors College — University Park, PA
Smeal College of Business — August 2012-May 2016
Major: Supply Chain and Information Systems — Dean's List
Minor: International Business

International Study

Universidad Pablo de Olavide, de Sevilla — Seville, Spain
- Studied International Business, Spanish history and culture — January 2015-May 2015
- Experienced total cultural and language immersion through a Spanish speaking homestay

Work Experience

L'Oreal Consumer Products Division — Cranbury, NJ
Operations Intern — May 2015-August 2015
- Extracted data and ran reports daily in order to track invoices and progress
- Reduced the number of invoice errors and manual touches required through process and system improvements
- Utilized Syncada Freight Payment System, TMS, and Microsoft Excel
- Developed a process to find and solve invoice errors that will be used in the future to increase budget accuracy
- Acquired greater networking and presentation skill through events and final presentation to senior management
- Gained insight on many aspects of the supply chain through tours of the distribution center, R&I Labs, and manufacturing facility

Penn State All-Sports Museum — University Park, PA
Event Staff — September 2013- September 2016
- Plan and organize events at the museum in order to ensure efficiency
- Assist the Programming and Education Coordinator with projects and educational programs
- Gathers and allocates supplies for each event ahead of time to guarantee orderliness

Camp Seneca Lake — Penn Yan, NY
Associate Program Director, Logistics — June 2014-August 2014
- Managed a budget of over $50,000, finished under-budget by comparing prices and finding alternatives
- Tracked all programming inventory, planned purchases and executed distribution of materials throughout camp
- Directed logistics for all camp programs on a daily and long term basis

Leadership/ Activities

Alpha Omicron PI Sorority — University Park, PA
Vice President of Chapter Development — September 2012-May 2016
- Facilitates the building of relationships among members
- Handles all conflict within the chapter and alleviates all minor and major issues
- Implemented a semester long program to keep members retained and engaged

Thon Chair
- Leader of fundraising efforts for an organization of 200 members; raised over $267,000 for pediatric cancer
- Planned canning trips for members which spread across the Northeast and accounted for $70,000 of year total
- Prepared schedule and coordinated logistics for events leading up to Thon, a 46 hour dance marathon

Philanthropy Chair
- Chair of annual philanthropic event which raises over $1,000 every year for Arthritis Research
- Communicates with corporate sponsors and local organizations to expand the event
- Leads and allocates committee members to help increase fundraising efforts and efficiency of the event

Phi Gamma Nu Fraternity — University Park, PA
Member — January 2013-May 2016
- Participate in both professional development events as well as philanthropy events
- Help recruit members in order to ensure the expansion and growth of the business fraternity

Pledge Class Philanthropy Chair
- Elected as chair of event to plan and run the pledge class philanthropy
- Communicated with local charities as well as fraternity members to organize event

Projects

- Consumer Goods: Third Party Special Pack Integration Project — January 2014-May 2014
- Grocery: Distribution Center Space Utilization Project — September 2014-December 2014
- Material Manufacturer: Inbound Freight and Materials Analysis — September 2014-December 2014
- Consumer Goods: Freight Payment System Analysis and Process Improvement — May 2015-August 2015