3D Printing's Impact on the Metalworking Industry

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Abstract

This project qualitatively estimates the potential impact of 3D printing on the United States metalworking industry. The adoption rate of 3D printing has been increasing in the last few years. On one side are businesses with long development and production lead times, competing in fast-paced industries. Moreover, some businesses are in the situation in which they need to reduce their supply chain complexity, to reduce costs and lead times. On the other side are businesses that are exploring the capabilities of Additive Manufacturing (AM) in their relationships with individual customers. A good example is the health care industry, where the need for customized implants like orthopedic replacement parts and tooth crowns has made this industry an early adopter.

Using data collected through site visits, an online survey sent to the sponsoring company's main customers, as well as interviews with companies currently using the traditional material removal manufacturing process and companies basing a large part of their operation on 3D printing, we studied the trends, main points of attraction, and barriers to AM adoption.

Our analysis suggests that 3D printing will be mainly used for prototyping, at least in the next 3 to 5 years. While some companies, especially in the health care industry, also are using it for their daily operations, almost no survey respondent envisioned using 3DP for mass production. Currently, the main barriers to AM adoption are the high initial investment (a barrier that probably will be broken in the next years, as the adoption of the technology increases) and the limited variety of metals available.

The key benefits that business expect to derive from using 3DP are reduced costs and lead time. In today's globally competitive market, being able to respond fast while keeping competitive prices could be a key differentiation factor, and may help adopters achieve that.

Finally, our study also indicates the size of the companies that are more likely to adopted 3DP. Small business (1 to 50 employees) are most likely to adopt, followed by very large business (with more than 1000 employees). The adoption horizon is almost evenly distributed among the next one to three years, the next 3 to five years and the next 5 to 10 years.

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SUMMARY

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1. Introduction and motivation

In this section we give a brief overview of the history of additive manufacturing in the metal industry. We describe the biggest challenges the technology must overcome to increase its market penetration, the areas in which it is most likely to be adopted, and the applications that appear to be more productive for practitioners to adopt. We also define the research motivation from the project sponsor business perspective.

1.1 What is 3D printing?

3D printing or additive manufacturing is a process in which materials are joined to create a three-dimensional solid object (Excell, 2013). This is done using a uses data computer-aided-design (CAD) software to direct where the metallic powder layers should be placed, forming the desired shapes. The process can create objects in almost any shape or geometry. Solid objects are typically produced using an electronic data source such as an Additive Manufacturing File (AMF) (Taufik & Jain, Role of Build Orientation in Layered Manufacturing: a Review, 2014). As the term additive manufacture implies, the process is done by adding layers of material to create the desired shape (GE Additive, 2018). The terms additive manufacturing and 3D printing are both used widely in articles and literatures, given that they are synonyms (The Technology House, 2014). In this paper, we will use both terms interchangeably.

1.2 History of 3D printing

In the 1980s, early additive manufacturing materials and equipment were developed (Bird, 2012). In 1981, two additive manufacturing methods for fabricating 3D plastic models with photo-hardening were invented by Hideo Kodama of Nagoya Municipal Industrial Research. A mask pattern or a scanning fiber transmitter is used to control the UV exposure area (Kodama, 1981). In July 1984, three French inventors filed a patent for the stereolithography process but it was abandoned by the French General Electric Company (now Alcatel-Alsthom): "lack of business perspective" was the claimed reason (Moussion, 2014).

To date, most 3D printers use fused deposition modeling technology, which is a special application of plastic extrusion, developed by S. Scott Crump and commercialized by Stratsys, his company. The first FDM (Fused Deposition Modeling) machine was marketed in 1992. Developed at MIT in 1993, the term 3D printing originally referred to a powder bed process employing inkjet print heads. The technology was commercialized by Soligen Technologies, Extrude Hone Corporation, and Z Corporation.

Additive manufacturing processes for metal started in the 1980s and 1990s. At the time, metalworking was done by processes called subtractive or non-additive (casting, fabrication, stamping, and machining). However, the automated technique that added metal began to challenge the original manufacturing process. By the mid-1990s, new technologies for material deposition including micro casting and sprayed materials (Beck, Fritz, Siewiorek, & Weiss, 1992) were developed at Stanford and Carnegie Mellon University (Amon, Beuth, Weiss, Merz, & Prinz, 1998). It is mentioned in various studies cited in this report that metal removal will no longer be the only metal working process: 3D processes will transform raw materials into a desired shape.

1.3 Advantages of 3D printing over traditional manufacturing techniques

3D Hubs, a website specialized in 3D printing, suggests that many benefits can be derived from using 3D printing to produce products. These advantages discussed in this section apply to any industry. According to 3D Hubs (Redwood, n.d.), these are the key advantages of 3D printing:

- **Speed**: one key advantage of additive manufacturing is the overall lower cycle time of material acquisition, design, production, and finishing. It is mentioned that design can be uploaded from a CAD model and printed in only a few hours, whereas a traditional manufacturing process could take days or weeks to make a prototype. This will allow for rapid prototyping and development of design ideas (Redwood, n.d.).
- **Single step manufacture**: 3D printing enables a manufacturer to produce products very effectively (Figure 1). Traditionally most parts require many manufacturing steps which could affect the quality and manufacturability of the design. Additive manufacturing machines could complete a creation of product in single step, which greatly reduces the dependency on different manufacturing processes (machining, welding, painting), providing designers greater control over the final product (Redwood, n.d.).

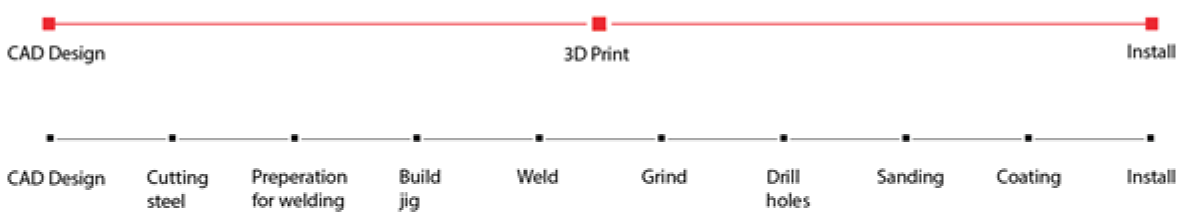

Figure 1 - Manufacturing steps (Source: 3D Hubs)

- **Cost at low volume production**: At low volumes of unit production, 3D printing is cost competitive compared to traditional manufacturing process, when considering the individual unit cost. This makes creating prototypes with 3D printing significantly cheaper than other alternative methods (e.g. injection molding) and often competitive for manufacturing one off parts. However, traditional techniques become more cost effective as volume increases and the high set up cost are justified by the large production volume. There are three categories of cost to manufacture (Redwood, n.d.):
    - *Machine operation cost*: 3D printer uses the same amount of power as a laptop computer. Industrial AM technologies could consume a high amount of energy to create a single part. Nonetheless, it allows for higher efficiency and turnaround given the ability to

produce complex geometries in a single step. Typically, machine operation cost gives the lowest contribution to overall cost to manufacture (Redwood, n.d.).

  - *Material cost*: This cost component varies by technology. Material costs are the biggest contributor to the cost of manufacturing. The range of materials available make comparison of material cost between traditional and additive manufacturing difficult (Redwood, n.d.).
  - *Labor cost*: This is one of the main advantages of 3D printing. Most 3D printers only require an operator to press a button and the printer will follow an automated process to make a part. With traditional manufacturing techniques, highly skilled machinists and operators are required. This makes the labor cost of 3D printing almost zero (Redwood, n.d.).

- **Complexity and design freedom**: Additive manufacturing gives designers a large amount of design freedom and allows for creation of very complex geometries. As the parts are created one layer at a time, design requirements such as draft angles, undercuts and tool access, are not applicable (Redwood, n.d.).
- **Customization**: 3D printing allows for design freedom and also complete customization of the designs. Given its high performance when building one part at a time, it is suitable for one-off production. The medical and dental industries have embraced these concepts for the creation of custom prosthetics (Redwood, n.d.).
- **Risk mitigation**: 3D printing allows manufacturers to verify a design by printing a production-ready prototype before investing in expensive manufacturer facilities and equipment. This significantly reduce the risk in the prototyping process (Redwood, n.d.).
- **Sustainability**: Additive manufacturing techniques generally use materials only as needed to build a part, unlike subtractive techniques that remove a significant amount of materials from an initial block resulting in high amount of waste material. Thus, additive manufacturing produces very little waste (Redwood, n.d.).

1.4 3D printing application

3D printing has been used in medical, manufacturing, and other industries (Taufik & Jain, Additive Manufacturing: Current Scenario, 2016). Rapid prototyping was one of the earliest applications with the objective to reduce lead time and cost of prototype development of new devices. The prototypes were typically created by subtractive techniques such as CNC machining, milling, turning and grinding etc. (Vincent & Earls 2011). Later, the following applications of additive manufacturing were developed:

- *Food industry*: Many types of food can be created through additive manufacturing such as chocolate and candy and flat foods such as crackers, pasta, and pizza. The technology squeezes out food layer by layer into 3D objects
- *Clothing and apparel industry*: 3D printed bikinis, shoes, and dresses are made and experimented with by various fashion designers (Taufik & Jain, Additive Manufacturing: Current Scenario, 2016). Nike used 3D printing to prototype and produce football shoes (2012 Vapor Laser Talon) for

American football players and New Balance manufactured custom-fit shoes for athletes (Chochrek, 2017).

- *Automotive and aircraft industry*: Koenigsegg, a Swedish supercar manufacturer, announced in 2014 a supercar that utilizes many 3D printed components (Business Insider, 2014). GE Aviation revealed in 2017 that it designs a helicopter engine with 16 parts instead of 900 (Zelinski, 2017).
- *Medical industry*: Virtual planning of surgery and guidance using 3D printed and customized instruments is used in many areas of surgery, including total joint replacement and craniomaxillofacial reconstruction with great success (Poukens, 2008). Surgeons in Swansea, England used 3D printing to create parts to rebuild the face of a motorcyclist who had been seriously injured due to a road accident (BBC News, 2014).

1.5 Metal working industry

Metalworking began long before the Iron Age, and welding has undergone its share of developments throughout the centuries (Smith, 2014). However, the industry as we know today, started developing only in the 1940's with John T. Parson, the precursor of the CNC technology (computer numerical controls). He was a helicopter rotor manufacturer. Teaming with Frank Stulen, the two developed a method where one machinist would read the coordinates along an x and y-axis to two other machinists who would then make the cut. From there, they teamed with researchers at MIT to develop punch cards (Figure 2) that could be programmed with enough points to provide for fully automated machining (Hillis, 2017).

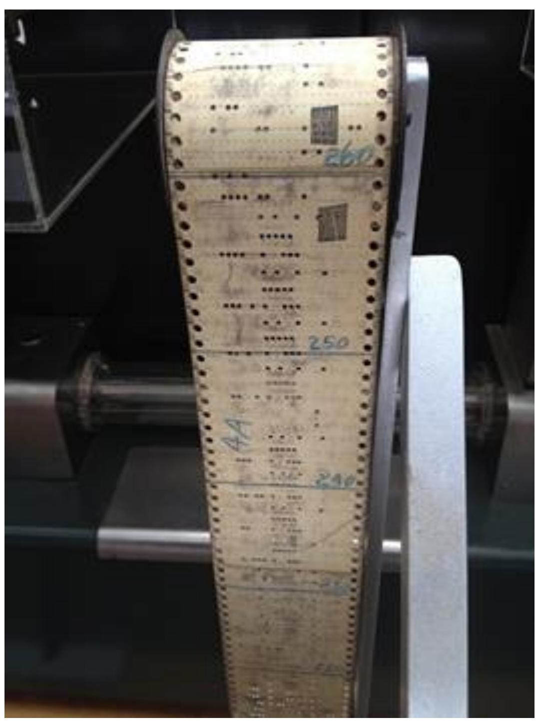

Figure 2 - A punch tape system

Slowly, over the following years, users started converting manual machine tools to numerical control (NC) by using motors that moved the turn-handles based on a punched tape system. After a while, these mechanisms were augmented with analog and, afterwards, digital computers, creating the first computer numerical controlled (CNC) machines (Hillis, 2017). Moving forward to the 1990 decade, CNC shops were busy retrofitting manual machines with motors, drivers and PC Based Controller turning them to full CNC. Since the demand was there, a boom in companies offering CNC retrofitting services happened. This opened up the door for manufacturers to speed up productivity and allowed them to incorporate CAD-CAM software to further simplify the CNC machining process. Throughout the 1990's, advancements in hardware technology continued to open the way for CAD-CAM software development, while allowing shops to take advantage of software because of falling prices. By the late 1990's, CAD-CAM was able to provide complete 2 & 3 Axis CNC programming technology (CAD-CAM and a Historical Look at CNC Machining, 2015).

Nowadays, the U.S. steel industry employs over 150,000 people across the country and supports, directly and indirectly over one million jobs nationwide. In 2014, the industry produced approximately to 100 million tons with a total value close to $75 billion (Hickey, 2015).

The supply chain of steel manufacturing still depends heavily on access to raw materials. In most cases, one will find steel manufacturers closer to the raw materials than to the consumers. For steel, the primary raw material is iron ore, which is now produced at several sites around the world. Close proximity to suppliers not only ensures a reliable source, but also significantly reduces time and transportation costs.

In contrast to many industries, in which supply chain managers prefer to keep inventory low, the steel industry functions in a different manner. Since the product is produced over several stages, the supply chain becomes one big ongoing process. For managers it is important to keep additional inventory in case an operation breakdown or a shutdown happens. With the additional inventory, the company can continue operating through a variety of disruptions.

As steel is considered a commodity throughout the entire process, today's steel supply chain managers need to utilize sophisticated logistics tools and best practices. Supply chain concepts such as contract management, commodity pricing and hedging are critical to an effective and fluid logistics process (Hickey, 2015).

There is also a shortage of qualified workers throughout the metalworking industries. Companies are having difficulty finding employees with the knowledge to program and operate the CNC machines. According to a study conducted in 2015 by the National Tooling and Machining Association (NTMA), 84 percent of its member companies reported having skilled positions open at their facilities, with a great shortage of engineers. Meanwhile, a similar organization, the Precision Metalworking Association (PMA), pointed that the average workforce age for the metalworking industry is from 41 to 60 years old (for 70 percent of its members companies). Those same companies mentioned that they have difficulty recruiting new workers (Hickey, 2015).

1.6 The project sponsor

The project sponsoring company is one of the large industrial equipment distributors in the US. The company distributes metalworking and maintenance, repair, and operations (MRO) products and services in North America. Currently, the sponsoring company has over 1 million products in its portfolio and provides supply chain and inventory management solutions to its customers. its customers range from small reliable shops to large manufacturing companies from various industries such as automotive, defense, aerospace, consumer products etc.

The advent of 3D printing, which profoundly changed the way manufacturer creates metal products with lower lead time and cost, could disrupt the traditional economics of manufacturing at the sponsoring company's industrial customer base. Thus, it is important for it to understand the variables that make 3D printing viable for certain products: either application, cost, complexity, performance specifications, size and safety, etc.

1.7 Research motivation

When asked what the key technology developments over the next five years would be, leaders of five important metal working industries mentioned the change in work materials and additive technology (Rooks, 2017).

The project sponsor is one of the main suppliers to the metal cutting industry. This industry could experience major changes in the next few years with the advance of additive manufacturing. Many benefits have been promised with the adoption of 3D printing, such as lower labor cost and shorter lead times. However, as with any new technology, the real improvements may or may not live up to the promised benefits. The sponsoring company wants to understand the real impact 3D printing has on its metal cutting customers. The objective of this work is, through a case study approach, to understand the real benefits perceived by companies that have already adopted additive manufacturing.

Consider this comment made by a metal shop owner: "In the '40s and '50s the numerical control was a quantum leap in manufacturing. It took us from manual machining to numerical machining with more control, accuracy, and the ability to adjust things. Additive is the same thing, a paradigm flip-flop where instead of removing material, we start with nothing and add. You are going to see more of it as design engineers discover the possibilities. Our market study on where this technology is going is phenomenal." (Sue, 2015).

As one can see, the additive manufacturing industry has evolved greatly during its short existence. New technologies are being developed on a daily basis and the number of 3D printer manufacturers has been increasing constantly in the last years. As one of the leading suppliers for the metalworking industry, the project sponsor has to understand the possible disruptions and potential opportunities that AM could bring to its business.

2. Background

This section provides background information on the metalworking industry, the benefits that most metalworking companies realize when adopting 3D printing, the real application of the technology, and lastly the challenges of implementing the technology.

2.1 Challenges in the supply chain of metalworking industry

The supply chains of industries related to metalworking have several challenges:

- **Aerospace & Defense**: The industry is in a transition from a steady state production model to a build-to-demand model that requires a higher level of supply chain agility (Becks). The challenge for the commercial aircraft now is to be able to ramp up supply chain to build more planes faster and arrange a multitude of components arriving at the same time. For example, the Boeing 747-8 has 6 million individual components manufactured in almost 30 countries by 550 suppliers. What is critical for the supply chain of this industry is the ability to track order creations, advanced shipment notifications, and shipments all the way to their assembly plants, as it diminishes the supply risks and helps the organization achieve target production rates. Companies are looking for ways to meet the demands of the market while managing costs more efficiently. Some companies have adopted 3D printing to produce high performance parts (3D Printing & the Aerospace Industry, n.d.).
- **Automotive industry**: Nowadays, auto-manufacturers are looking to innovate in a more efficient way, as designs, cost and functionality become important selection criteria from customers. Also, manufacturers are looking to reduce inventory, as a large quantity of components are sitting in stock in warehouses all around the world (Krauss, 2017). Other challenges from a supply chain standpoint are reducing turnaround time in the prototyping process, reduce consumption and waste during manufacturing. Lower production costs could allow the companies to transfer some of the cost-reduction benefits to the end-user (3D Printing in Automotive - Empowering Tomorrow’s Transportation, 2017).
- **Healthcare and Life Science Industry**: Today, manufacturers of medical devices are looking to improve lead times and reduce costs. Traditionally on average it takes 4-6 weeks to manufacture a device in aluminum and ship it to hospitals (The Importance of 3D Printing in Healthcare, 2017). Also, some devices and parts are needing to be customized to match patient needs, which results in longer lead times and higher production costs.

2.2 Benefits of 3D printing to metalworking industry

According to McKinsey & Company, there are four key benefits of 3D printing for those who adopt the technology over traditional metalworking process (Chalabyan, et al., 2017).

1. **Shorter value chain**: Only three steps are required in the additive manufacturing process. The first is producing the metal using traditional machining and casting processes. The second is the making of raw materials in the form of either powder or wire for the printer. Lastly, the 3-D printer melts the power to create the desired shape with finishing steps required in most cases. Key benefits of 3D printing are that need for standard inventory policy, complicated logistics, and long supply chains are minimal. If the printer is available, production can start immediately (Chalabyan, et al., 2017).
2. **Low waste**: 3D printers can create objects with minimal waste compared to the traditional metalworking process where large sheets of metals and materials cause extensive waste. 3D printer prints only the powder or wire that is required to build the component's structure layer by layer. Scrap rates for 3D printing are very minimal at only 1-3 percent. Moreover, the 3D printing process is less labor intensive and more sustainable (Chalabyan, et al., 2017).
3. **Greater design freedom**: As mentioned before, one of the key advantages of 3D printing is the capability to go beyond many design and manufacturing constraints. 3D printers can create previously impossible structures without having to assemble the components together like the traditional manufacturing techniques. For example, a metal rib cage can be custom-printed for a cancer patient. Moreover, complex 3D shapes can be printed with improved properties, as seen from 3D-printed lightweight car seats and airplane belt buckles. The design freedom provided by AM technologies (Figure 3) gives a new concept called Design for Additive Manufacturing (DFAM), which are design methods or tools (including topology optimization, pictured below) where product performance can be optimized to the capabilities of 3D printing technologies as opposed to traditional machining, which is much more limiting. (Chalabyan, et al., 2017).

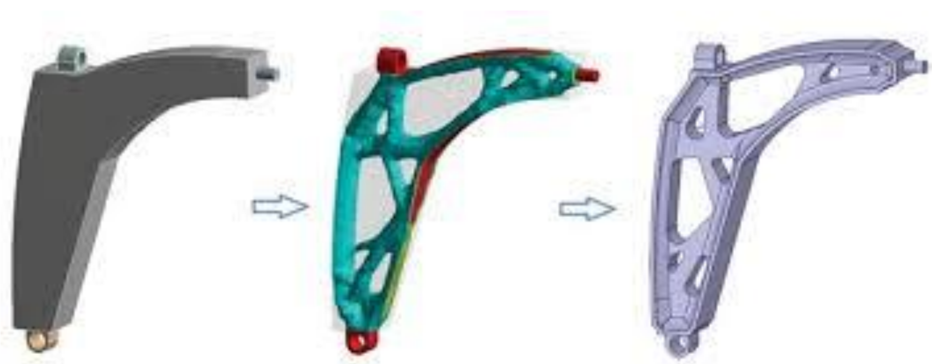

Figure 3 - Design improvement with 3DP

4. **Cost effectiveness at small scale**: For small production lots, 3D printing is generally more affordable than the traditional manufacturing process, as most metalworking facilities are set up for large-scale

production. Moreover, 3D printing can be set up with less investment than the traditional metalworking facility, given the main investment is just the printer itself (cost of a few thousand dollars though they can go up to $2M). 3D printing can establish just-in-time production, which makes it more attractive to those manufacturing highly customized parts in small batches who want to scale that production when needed (Chalabyan, et al., 2017).

2.3 Successful Applications

This section provides examples of successful adoption of the 3D printing technology by manufacturing companies to offer perspectives on what and how the benefits are realized in real applications.

2.3.1. PTooling

PTooling is a Canadian company that manufactures oilfield and aerospace components. They utilize AM for the aerospace production of aeroengines, landing gear/hydraulic systems, and high strength/low weight structural components. “Survival prompted us to get into additive,” said Marvin Fiebig, the PTooling owner and founder. “We’re still going strong, but if a company doesn’t do something unique or advance its capabilities, it will become a dinosaur”.

Even though PTooling leadership sees additive manufacturing as a promising technology, the company is not expecting to turn all its production into additive manufacturing. Their goal is to develop $20,000 and up programs with suppliers. If orders for quantities large enough to lower the price to $70 or $80 come in, they will produce them. The PTooling team believes that the process may not be worth much to a company that has a very small operation, but that a company with resources might spend $100,000 to save a million.

For the company, when a manufacturer is limited with prohibitively expensive alternatives—whether lead times, material costs or availability, design and engineering, or anything that makes a project undoable—it is a potential project for additive/subtractive manufacturing.

“With AM you can spread out the load and lighten the part. For example, the wing’s leading-edge formers can be redesigned to be wider to accomplish stability while weighing less” says Fiebig.

One example of a successful application made by PTooling was one jet engine with a component that required 23 parts in one assembly. With AM, it is now made as one part and with a 25 percent weight savings. Parts up to 23.6 in. by 15.7 in. and 1,322 lbs. can be built in their machine’s working room.

Combining AM and traditional cutting in one machine makes new applications and complex geometries possible at PTooling. The automatic change between laser metal deposition and milling operations allows the direct milling of sections of a part that cannot be accessed in its finished form. AM builds a section of the part, 5-axis milling creates internal features, and AM builds the next section.

Weeks of production can be knocked out, since no patterns or special tooling are needed. “A customer will come to me and say it would take 12 weeks to get patterns made for a casting or hours to develop tooling because the part would have to be fixtured. Those things aren’t needed with AM so we can deliver faster.”

Fiebig’s vision is the following: “We’re not going to blow the doors off standard machines--I wouldn’t want to do that--but if we can give a customer a newly designed component that meets their needs in four weeks instead of 20, they will probably opt for using the new technology. Basically, we can make a part that is 30 percent lighter, 50 percent stronger, produce it faster, and material costs will be cheaper because we’re not machining away the biggest portion of a material block.”

Right now, the traditional machines carry the profitability load. Fiebig expects that to change when the additive/subtractive machine reaches full production (Sue, 2015).

2.3.2. GE

A decade ago, engineers at CFM International, a joint venture between GE Aviation and France’s Safran Aircraft Engines, started designing a new, fuel-efficient jet engine for single-aisle passenger planes — the aircraft industry’s biggest market and one of its most lucrative.

CFM came up with a new engine that could dramatically reduce fuel consumption as well as emissions. A key to the breakthrough was the ultra complex interior of the of the engine’s fuel nozzles. Developed by GE Aviation, the nozzles’ tip sprays fuel into the jet engine’s combustor and help determine how efficient it is.

However, there was a problem. The tips’ interior geometry was too complex. It had more than 20 parts that had to be welded and brazed together. It was almost impossible to make. “We tried to cast it eight times, and we failed every time,” Ehteshami, a GE engineer recalls.

Therefore, after several attempts, they decided to try to 3D print it. The 3D printed nozzle met the team’s wildest expectations. It not only combined all 20 parts into a single unit, but it also weighed 25 percent less than an ordinary nozzle and was more than five times as durable. “In the design of jet engines, complexity used to be expensive. However, additive allows you to get sophisticated and reduce costs at the same time. This is an engineer’s dream. I never imagined that this would be possible”, says Ehteshami after many years working with 3D printed parts.

After the nozzle success, GE’s engineers moved on to the next challenge. A different team decided to create a brand-new advance turboprop engine, or ATP. Using additive manufacturing, they consolidated 855 components into just a dozen parts. The simpler design reduced weight, improved fuel burn by as much as 20 percent and achieved 10 percent more power. Using 3D printing for rapid prototyping, the team was also able to cut development time by a third. Last summer, Textron Aviation picked the engine to power its new plane, the Cessna Denali (Kellner, 2017).

Figure 4 presents some applications of 3D printing currently being used by GE.

3-D printing in aerospace

The aerospace industry is one of the early adopters of 3-D printing for metal-part production, particularly in turbines and other components that use nickel alloys or titanium. The following are examples of successful parts manufactured to date using the technology.

LEAP engine fuel nozzle. Tapping into the design flexibility that 3-D printing offers, General Electric and Safran jointly developed a fuel nozzle that is 25 percent lighter but five times stronger than an earlier design.[1] The part has a hollow interior, which makes it much lighter than the solid-mass version, delivering significant savings in fuel cost. Additionally, the new nozzle replaces 19 different parts that had to be assembled to create the previous product. GE has ordered 8,500 LEAP engines, each equipped with 19 of these nozzles.[2]

GE90 T25 sensor housing. This sensor housing, built by General Electric, is a complex part used in high-pressure compressors of the GE90 family of engines. In the past, it took years to go from order to finished product, making technological advancement a slow and tedious process. By printing the part using a cobalt-chrome alloy in the powder bed fusion process, GE was able to cut the production time down to a few months, allowing for much quicker iteration and fine-tuning of the design. The T25 was the first 3-D–printed commercial aircraft part to be certified by the US Federal Aviation Administration, and about 700 engines will be retrofitted with the new housing.[3]

Figure 4 - AM applications in use at GE

2.3.3. MTU

MTU is a Munich-based company with an annual revenue of 5 billion euros. It is Germany's leading engine manufacturer. The company engages in the design, development, manufacture, marketing and support of commercial and military aircraft engines in all thrust and power categories and stationary gas turbines (MTU Aero Engines, 2018). In 2015, MTU Aero Engines announced that, in a partnership with EOS Technologies, it would use additive manufacturing for series production of a nickel alloy borescope bosses (Figure 4) in order to help the Airbus achieve its 15 per cent reduction in fuel consumption for the A320neo. They form part of the turbine housing for the A320neo's GTF engine and allow the blading to be inspected at intervals for wear and damage using an endoscope, which in the aerospace sector is termed a borescope.

Previously, the borescope bosses were either cast or milled from solid. The decisive factor in migrating to 3DP was the anticipated cost advantage. The cost was reduced in the development and production stages. The Pratt & Whitney PW1100G-JM is the first aero engine to be equipped with borescope bosses produced by additive manufacturing. Sixteen parts per build are forecasted, totaling up to 2,000 parts per year. The percentage cost saving compared to previously established manufacturing processes is expected to be in double figures and the quality level seems to be high. MTU and EOS are working together to optimize the finish of the component surface.

As MTU is a producer of raw materials, the company was able to develop a new process chain, which has been integrated into the manufacturing system. It is underpinned by a control system specifically developed by MTU. Online monitoring captures each individual production step and layer. In addition, new quality assurance procedures were introduced, such as optical tomography. The German Federal Aviation Authority has certified the EOS manufacturing platform (MTU Aero Engines Uses 3D Printing for Series Component Production, 2015).

Nickel alloy borescope boss. The borescope boss is a part of the aircraft engine housing that allows the blading to be inspected for wear and damage using an endoscope (which in the aerospace sector is called a borescope). This part, produced by MTU on machines delivered by EOS, is used in Pratt & Whitney engines that power the Airbus A320neo. Previously, the borescope boss was cast or milled from solid material. By switching to 3-D printing, MTU expects to reduce costs both during the develpment stages and in the final production. The company plans series production of 2,000 parts per year, and expects to save more than 10 percent over traditional manufacturing cost.[4]

Figure 5 - MTU nickel alloy borescope bosses

2.4 Current challenges of 3D printing

Even though additive manufacturing is becoming more popular and its usage more common, there are still some barriers to make this technology become as common as traditional CNC machinery.

1. *Materials variety*

The more materials options available, the greater the number of proprieties that can be embedded into the final product. Traditionally, AM applications have been restricted due to the limitations on the materials that can be used. While traditional CNC has a wide range of materials available, such as alloys, metals and composites, 3DP is relatively new to have had so many developments. The materials for AM are still costly, given their limited application (Deloitte University Press, 2014).

Besides, most printers cannot mix materials within one item. Even though some 3D printers makers claimed to have had mixed materials successfully during the printing process, there are no available commercial 3D printers that can do it. The ability to mix materials is a focus of intense research through the whole value chain (Chalabyan, et al., 2017).

However, research has been steadily progressing to expand the portfolio of available materials. For example, researchers at the University of Warwick have developed a low-cost composite material that can be used specifically for additively manufacturing electronic components (Deloitte University Press, 2014).

2. *Cost of raw materials*

Apart from new materials, new technologies that produce existing materials in a cost-effective way also have an impact on the adoption of AM. Titanium is a good example, being a material with low density, high strength, and corrosion resistance, it has a strong appeal in the automotive industry for its ability to make lightweight, high-performance parts. Yet, its usage is limited due to the prohibitive cost of production of the metal powder, costing about $200–400 per kilogram (Deloitte University Press, 2014).

Powder production today is inefficient mainly for two reasons: its small scale and the fact that only 50 percent of the atomized powder is of sufficient quality. Irregular and inconsistent particle size are the main reasons for this low yield. Most existing powder atomizers produce powders too coarse for many applications. The industry is working to improve the yield rate, which will help drive down the total cost and increase output of 3-D printing processes. Yield rates above 90 percent were achieved in tests made by precious metal manufacturers, which creates expectations for the metal powder cost to drop in the near future (Chalabyan, et al., 2017).

3. *Product quality and reduced post processing*

Parts produced through most AM technologies occasionally show variability due to thermal stress or the presence of voids. This results in lower repeatability, which is a challenge for high-volume industries such as automotive where quality and reliability are extremely important. One way to tackle this challenge is through machine qualification, where companies follow industry standards as well as those of the AM technology providers.

Another big concern about using 3D printing parts is that the dimensional accuracy is low when compared to parts produced with the traditional manufacturing process. For example, researchers have found that sand molds made by AM could lead to reduced dimensional accuracy in metal casting tools. The surface finish of AM is of the order of 10-100 microns, which is normally considered out of the high-precision range. Even though not every industry requires high precision, finish quality might become a factor for high-performance components. Nevertheless, AM techniques such as electron beam melting promise to significantly enhance surface finish (Deloitte University Press, 2014).

Most components manufactured through AM require some form of post processing, which involves removing unused material, improving surface finish, and removing support material. For simple parts, the amount of post processing is not significant. However, as the size and complexity of the components increase, it may become necessary to improve post processing quality and reliability for AM to be used on a larger scale. This seems to be particularly important for companies seeking to use 3D printing in the production of final versions of critical components such as engine manifolds.

Variability and finish quality concerns could possibly be solved by hybrid manufacturing. Hybrid manufacturing is the combination of AM with traditional techniques such as milling and forging. This would enable part production through a combination of techniques, amplifying the possibilities. One example of a hybrid manufacturing technique is ultrasonic additive manufacturing, an advanced technology based on AM, using sound, that combines additive (ultrasonic welding) with subtractive (CNC milling) techniques to create metal parts. The use of 3D printing allows these parts to have special features such as embedded components, latticed or hollow structures, complex geometries, and multilateral combinations, and the use of CNC milling ensures uniform finish quality (Deloitte University Press, 2014).

4. *Manufacturing large parts*

One of the limitations of AM's utility is the limited size of what can be printed, either for metals or plastics (Deloitte University Press, 2014). Parts larger than 30 cm^2 are difficult to produce using existing 3-D printers (Chalabyan, et al., 2017). Given this restriction, larger components such as body panels that are produced through AM still have to be attached together through processes such as welding or mechanical joining (Deloitte University Press, 2014).

To overcome this, low-cost AM technologies that can support larger build sizes for metal parts have to be developed. There is already significant research in progress. "Big area additive manufacturing," under development by Oak Ridge National Laboratory and Lockheed Martin, has the potential to manufacture products without any restrictions on size. Another example is the mammoth stereolithography process developed by Materialize, which has a build envelope of 2,100 mm x 680 mm x 800 mm— big enough to manufacture most of the large components of an automobile (Deloitte University Press, 2014).

As mentioned above, the supply chain of industries such aerospace, automotive and healthcare is going through a transformation. The need to shorten the lead times and increase innovation was never so stressed, a fact that makes these sectors big candidates to the adoption of 3D printing.

Besides shortening the value chain and increasing design freedom, benefits involving waste reduction and cost effectiveness for small scale productions could potentially be achieved with AM. We already see some industries adopting this new technology, especially the aerospace sector with players like PTooling, GE and MTU.

As any new technology, 3D printing still presents some barriers to adoption. The most common reasons for business to not adopt AM is the limited variety of materials, the high cost of raw materials when compared to the raw materials of traditional metalworking industry, the lack of procedures and definition of quality standards and the limited printing size.

3. Literature Review

Here we will explore the previous research and studies about 3D printing and the application of the technology, especially in the metalworking industry. However, the literature that outlines the impact of 3D printing on the metalworking industry is relatively scarce, since most of the papers regarding 3D printing are focused on general applications, rather than on a specific industry. There is research about the impact of 3D printing on supply chains in general but there was still limited amount of data available and many assumptions are made to predict the impact. In our study, we will estimate the potential adoption of the technology within this specific industry and the potential revenue changes for the sponsoring company.

Predicting the impact of a new technology in the industry is very difficult. Bhasin and Bodla (2014) discuss the possible impacts of additive manufacturing on global supply chains. In a 2014 paper, they point the limited amount of data available to drive conclusions of the possibilities that 3D printing could bring, a problem that the authors of the current study also faced. On their work, Bhasin and Bodla focus on the automotive and life science industries. They evaluate AM for a wide range of materials, such as metals and plastics. On a quantitative approach, they model the cost on both industries to calculate the threshold where 3D printing would become financially attractive. One of the main assumptions made in the cost model is that, in the future, companies will be able to place 3D printers wherever they need. Given the scenario we have today, this still is not a reality for the metalworking industry, since some post processing work is necessary. Bhasin and Bodla (2014) consider that the main feature that would make a company migrate from traditional manufacturing to additive manufacturing is the cost component. In the present work, a more qualitative approach is used. Features such as design freedom and the possibility of complexity reduction are considered as relevant as cost in a business decision to change its processes. Besides, the current work is focused solely at metal AM, while in Bhasin and Bodla's paper plastic 3D printing plays a key role in setting the threshold.

Minguella-Canela et. al (2017) evaluate the production strategies and degree of postponement when incorporating additive manufacturing into supply chains. They evaluate in which point of the manufacturing process would be ideal to stop the production and wait for customer's specific demand. To do this, they use a numerical modeling algorithm. The products chosen for the study are all manufactured in the traditional way, so in order to estimate the ideal point for AM several assumptions are made. Many materials are evaluated, such as plastic, metal and ceramics. Minguella-Canela et. all (2017) also assume that no post processing work is needed once the item is 3D printed, which, as mentioned before, currently is not the reality for the metalworking industry. In comparison, the present work also aims to evaluate if suppliers are willing to replace their entire manufacturing process with AM or want to use it just for customization, making it a good tool to evaluate some of the assumptions made by Minguella-Canela et. al. (2017).

Huang, Liu, Mokasdar & Hou (2012) point some of the main benefits of AM as the possibility to redesign products with less components (fact that was already proven by GE), to improve efficiency in lean supply chain and waste reduction. They believe that 3D printing is especially interesting for slow movers (items with low demand), the same claim made by Bhasin and Bodla (2014). On this research, due to resource and data limitations, we are not able to evaluate AM capabilities down to the SKU level. Another interesting point brought by Huang, Liu, Mokasdar and Hou (2012) is the fact that, to better utilize AM, it is interesting to produce parts in a centralized location, thus aggregating the demand. As a downside, it would increase the response time for new orders. This is aligned with what the authors of this paper intend to evaluate with the research.

Mathias and Rao (2015) identify 3D printing's implications to business and evaluate current users and potential customers. Consumer 3D printing survey was conducted on 66 participants, and five businesses were interviewed. The survey showed that all business customers had experiences and knowledge about 3D printing technology, while only a small fraction of consumers have used 3D printers. For consumers, more than 60% are not willing to buy the printer if the price is higher than $299. On the business side, the researcher separated the companies that have adopted the technology into two groups: 3D printing service companies and R&D driven companies. 3D printing service companies were the ones that focused on education, while R&D driven companies were the ones that uses the technology to enhance the efficiency of R&D process. For the 3D printing service companies, the 3D printed output is used as a final product, while for the R&D driven companies, the 3D printed output is used for R&D purposes only. The study reveals interesting application of the technology on both consumers and businesses.

The Wohlers Report on the 3D printing and additive manufacturing state of the industry estimated the growth of metal 3D printing technology. In 2016, estimated 957 metal 3D printing machines were sold, compared to 808 machines in 2015. The growth at this period is estimated to be at 18.6%. Most of the companies who reportedly bought the machines are new entrants and large OEM. Metal 3D printing has started to move beyond prototyping to final part production, seeing 40% higher machine sales for the same period in 2015. The report points out that the metal additive manufacturing is well-suited to production applications as it offers similar or better material properties. Moreover, metal 3D printing can substantially help reduce waste.

Overall, although the researches that covers the impact of 3D printing on the metalworking industries is limited, the literature reviews give us some interesting insights with respect to the potential impact on supply chains, the application of the technology, the potential adoption, and the current and future market landscape of the technology.

4. Research methodology

To study the impact of additive manufacturing on the project sponsor, we studied current metalworking companies that have adopted the technology and evaluated the benefits that they realized. We compared the real-world benefits with the ones promised in the literature to understand 3D printing capabilities. We then used the information to predict the impact on other customers with similar characteristics. To collect data, we conducted site visits to observe the current operations of traditional metalworking industry and business in which additive manufacturing is already a reality. We also interviewed key stakeholders in the sponsoring company customers, and conducted secondary research to understand the industry landscape, applications and trends.

4.1 Data collection

Data collection was done through customer site visits and face-to-face interviews, phone interviews, and secondary research.

4.1.1 Site visits

Two groups were visited throughout the research project: customers that use only traditional CNC machinery and customers that have already adopted 3DP.

First, we conducted site visits to customers of the project sponsor to understand the current metalworking industry, in terms of how the components are manufactured by the traditional process, the reason the manufacturing processes were set up this way and the challenges that manufacturers face. During our visits we observed that highly customized parts required multiple manufacturing steps to produce. In most cases, the original raw materials would be put in the machines and would go through multiple cutting processes to create the desired shape. To make sure that the components meet required specifications, quality assurance steps are in place along to way. For example, we saw how the cooling machinery in the aerospace industry is made: a process that requires approximately three days to create the parts and in which 90 percent of the material is wasted. During the visits, a salesperson from the sponsoring and the production manager helped explain the process and provide insights as to why the processes were set up this way.

On the other side of the spectrum, we visited customers from the sponsoring company who have adopted 3D printing technology to understand the application of the technology, the benefits they realized or not, and the challenges and limitations the technology still has. Through these visits we observed steps required to 3D print parts, which includes software modeling, transferring 3D file to the printer, setting up the machines, producing the components, removing parts from the base, and the finishing process, which might include milling and other traditional CNC machining steps.

4.1.2 Telephone interviews

In addition to site visits we also conducted telephone interviews to component manufacturers, 3D printing software developers, and a 3D printer manufacturing company. The interviews helped us gain insights during the data collection period. All respondents requested anonymity but allowed us to use their comments.

4.1.3. Survey

To understand how inclined customers are to adopt 3D printing and how the project sponsor's revenue profile might change in the future, we conducted an online survey with 133 customers. The survey was structured to obtain insights from the customers such as how familiar they are with 3D printing, how likely they are to implement the technology, where they are in the implementation process, and to understand the benefits and barriers in the adoption of 3D printing. We were also looking to observe whether there are patterns of adoption in particular industries and company sizes. The survey questions can be found below:

1. What industry are you primarily serving?

- Automotive & Transportation
- Aerospace & Defense
- Healthcare, Medical Devices & Pharmaceuticals
- Machinery, Equipment & Parts
- Energy
- Materials
- Consumer Products
- Chemicals
- Food & Beverage
- Others

2. How many employees do you have?

- 1-50
- 51-150
- 151-500
- 501-1,000
- More than 1,000

3. How much do you know about 3D printing?

- ◯ I am not familiar with 3D printing
- ◯ I have heard about 3D printing but I don't know much about it
- ◯ I am familiar with 3D printing and I am aware of the process
- ◯ I am very familiar with 3D printing, and am aware of this process and benefits
- ◯ I am very familiar with 3D printing, and have used or currently using 3D printing

4. How likely are you to adopt 3D printing in the future, on a scale of 1-10?

Not likely to adopt				Adopt 50% of the manufacturing line					Replace 100% of the manufacturing line with 3D printing
☆	☆	☆	☆	☆	☆	☆	☆	☆	☆

5. If you are likely to adopt it, for what application are you considering using the 3D printing technology

- ☐ Prototyping
- ☐ Customized Production
- ☐ Mass Production

6. If you are likely to adopt the technology, which stage are you currently in?

- ◯ We have decided to adopt but we haven't started the project
- ◯ We are developing the plans to implement the technology
- ◯ We are in the process of implementing the technology for our business
- ◯ We have set up and are testing and evaluating the effectiveness of the technology
- ◯ We finished the implementation and 3D printing has become a part of our operations

7. If your answer is likely to adopt, how soon do you think you will adopt it?

- Short term (within 1-3 years)
- Medium term (within 3-5 years)
- Long term (within 5-10 years)

8. If you are likely to adopt 3D printing, what are the reasons? What benefits are the most important to you? Please rank the importance from highest to lowest (1 = most important, 7 = least important)

- Cost reduction
- Lead time reduction
- Waste reduction
- Design freedom
- Ability to customize products
- Complexity reduction (Production steps reduction)
- Environmentally friendly

9. What do you think are the main barriers to adopt 3D printing? Please rank from the biggest barrier to the smallest barrier (1 = biggest barrier, 7 = smallest barrier)

- High initial capital investment
- Skilled labor requirement
- Limited type of metals available for 3D printing
- Lack of quality standards
- Potentially higher raw materials costs
- Limitation on size of products 3D printing can make
- Limited number of 3D printer manufacturers

10. Please provide comments on why the top 3 benefits and the top 3 barriers are the most relevant to you (optional)

4.1.4. Secondary research (Industry report and internet)

Industry reports from several sources, such as Senvol, Wohlers, Deloitte and McKinsey, helped us understand the current market landscape, including size, growth potential, and competitive landscape. Additionally, these sources provided insights into application and market trends of 3D printing. Internet articles from reliable sources also confirmed some of the benefits of the technology to metalworking industry. Overall secondary research data was helpful in fulfilling the data gaps where we could not find from the primary data sources.

5. Results and analysis

Here we compare the data obtained by the survey with the information collected during site visits, phone interviews and secondary research. To contact people who answered the survey, a database provided by the sponsoring company was used.

5.1. Overview of the data set

After the survey was launched, we received 133 responses out of 20,000 customers, a response rate of approximately 0.006%. Due to the relatively low response rate, the data cannot be a statistical representative of the overall population as the confidence level is low. However, we drew some useful observations and insights from the survey that our sponsoring company can consider when prioritizing customer segments based on 3D printing opportunities and risk profile. These observations are presented in this section.

Table 1 shows the number of respondents that serve each industry. For example, 20 respondents indicated that they manufacture parts for aerospace companies.

Industry	Count
Aerospace & Defense	20
Automotive & Transportation	25
Consumer Products	5
Energy	4
Food & Beverage	1
Healthcare, Medical Devices & Pharmaceuticals	5
Machinery, Equipment & Parts	23
Materials	6
Others	17
(blank)	27
Grand Total	**133**

Table 1 - Respondents segmentation by industry

The data points from customers in the Food & Beverage and Energy industries will not be used given that only few data points were received. We use 5 as the cut-off point for the number of samples received, as fewer responses would not be enough to draw a conclusion. Overall, the combination of customer segments mirrors that of the sponsoring company customer profile, since we received more responses from customers in the Aerospace & Defense, Automotive, and Machinery, and Equipment & Parts industries than other industries. Customers in these industries make up a high percentage of sponsoring company revenue. These three segments contributed to over half of all the responses. Many respondents did not indicate their company and industry information.

In terms of the company size, we use number of employees as a proxy for company size. We found that most responses are from small and large businesses. This is because the sponsoring company has a strong presence among small shops. The number of responses by company size could be found in Table 2:

Number of employees	Count
1-50	38
51-150	15
151-1,000	32
More than 1,000	20
(blank)	28
Grand Total	**133**

Table 2 - Respondents segmentation by size

5.2. Overview of the results

The customers that answered the survey are spread among diverse industries, the largest groups being automotive and machinery and equipment & parts (23% and 21% respectively).
More than one-third are small business (between 0 to 50 employees), while other 40% is evenly distributed between medium size business (between 151 to 500 employees) and large business (more than a thousand employees).

Surprisingly, no respondent said he or she was not familiar with 3D Printing. 32% of the respondents claimed that they are familiar with 3D Printing and are aware of the process, while other 25% said that they are very familiar with 3D printing and have used or are currently using 3D printing.

When asked about the likelihood of adopting AM in their production lines, most business are not inclined to do it. Some may consider replacing up to 30% of their production line, but the majority currently are not considering adoption.

For the ones considering adoption, almost four fifths are considering using it for prototyping.

Regarding the adoption stage we have a very uneven scenario, as Figure 6 shows. While 40% have not even started a project to adopt it, a surprisingly high 24% are already using it as part of their operations.

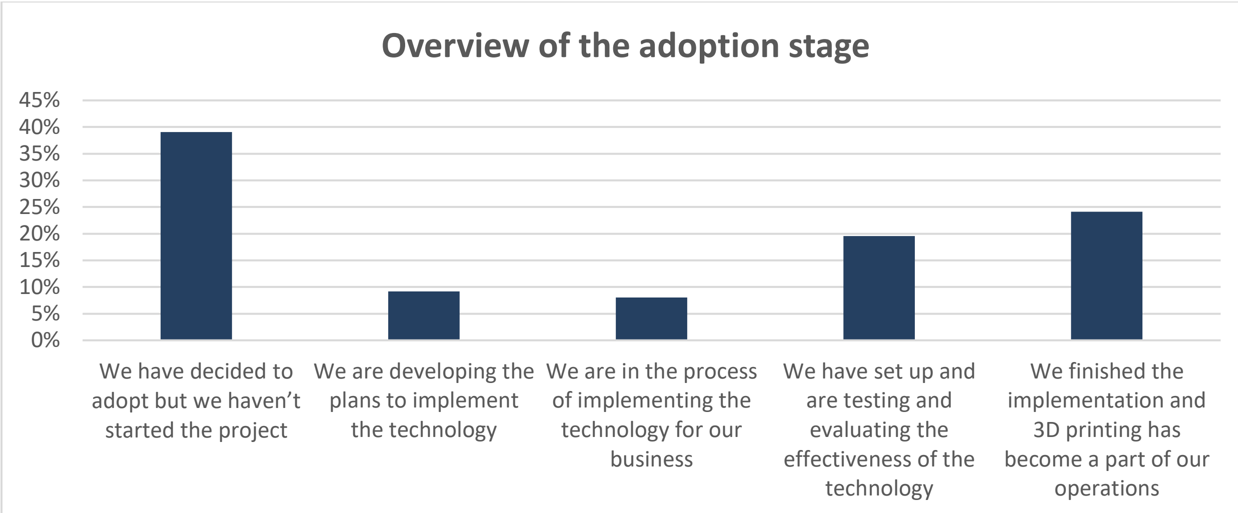

Figure 6 - Adoption stage overview

So far, is also hard to predict a time frame for the adoption. Customers are almost evenly distributed between adopting within the next 3 years, in the next 3 to 5 years or in more time then the next five years.

Another goal of the research was to understand the biggest motivations for and barriers to a business adopting AM. We asked customers to rank the most/ least appealing reasons.
Not surprisingly, the main factors attracting business are cost reduction and lead time reduction. What is interesting is that design freedom is almost as attractive as lead time reduction, as shown in Figure 7.

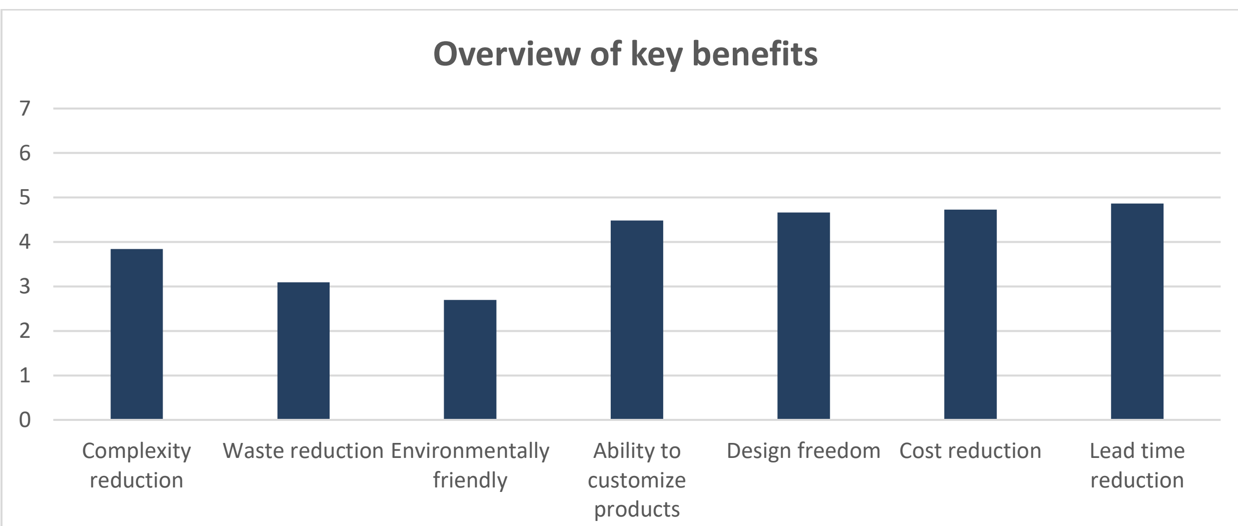

Figure 7 - Key benefits overview

One interesting finding is that 3D Printing could be environmentally friendly and reduce the amount of waste generated are the least attractive benefits that AM could bring.

When we look at the barriers, the reasons for not adopting are more evenly distributed as shown in Figure 8.

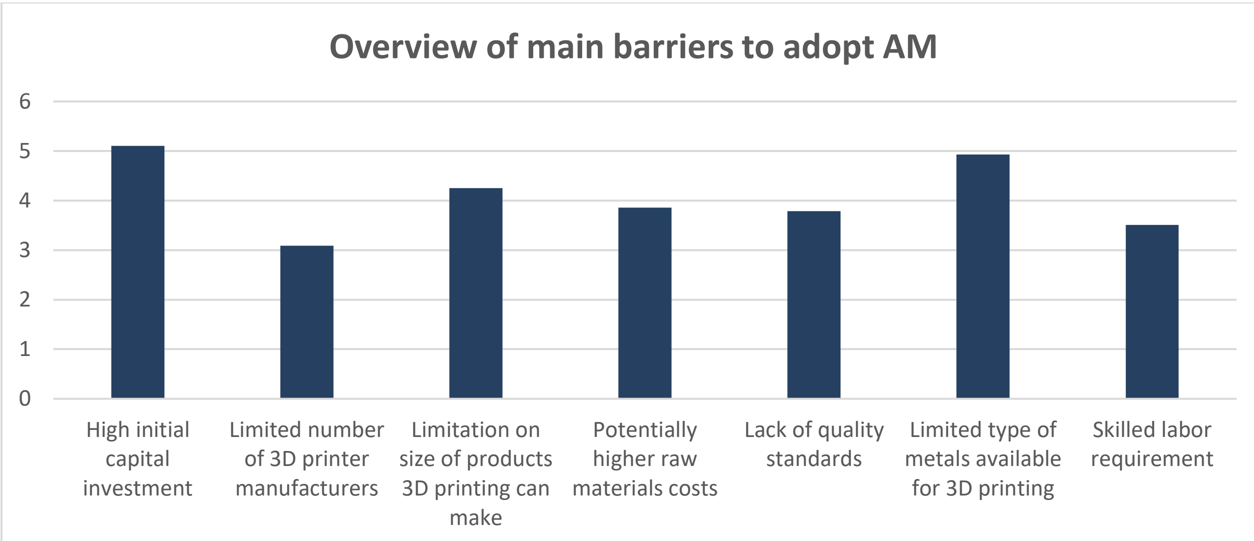

Figure 8 - Main barriers overview

The first barrier is the high initial investment, ranked as the number one reason for about 43% of the business. But all the other factors, except the limited number of 3D Printing manufacturers (which has the lowest rating), are relatively evenly distributed.

On the open questions we received some interesting answers that reflect how familiar with 3D printing each business is. While some people say that the precision is still not good enough and that additional finishing is needed, others state that they do not have enough familiarity with the technology.

In general, the answers reflect what the literature says, with the big surprise being how many businesses are already using or implementing AM.

5.3. Analysis of the results by industry segment

When looking by segment, we can see that players in the Aerospace, Automotive, and Machinery industries seem to be more familiar with 3D printing, and some are currently using the technology in part of their manufacturing processes, as shown in Figure 9. This is in line with what we have found in the secondary research in that the application of 3D printing are more match with what they manufacture, i.e. customized parts and components etc. Also, we see higher familiarity in Healthcare industries given the need for customization in the industry.

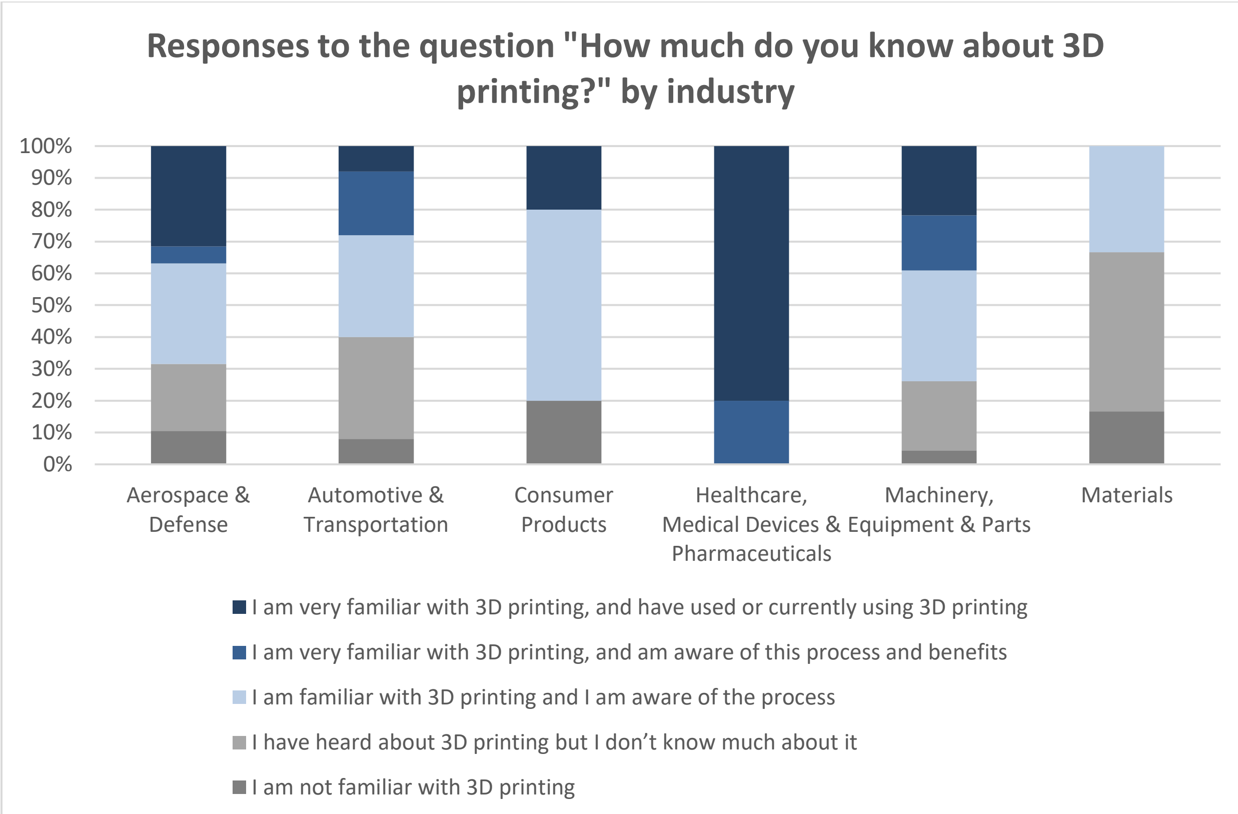

Figure 9 - Awareness of 3DP segmented by industry

In addition to the knowledge about 3D printing, we also asked how likely the company will adopt the technology. As a result, we see higher potential adoption within the industries that are more familiar or are using the technology: Aerospace, Automotive, Healthcare, and Machinery. Most companies will not replace the entire or most of the manufacturing line with 3D printing, but rather just 20-50% of it, as shown in Figure 10. This is in line with what we found from the interviews that due to materials and quality constraints, 3D printing will be used as a “supplemental” process and won’t replace the traditional methods of manufacturing parts. What we found more common is the use of 3D printing to build up the components and then CNC machine for finishing.

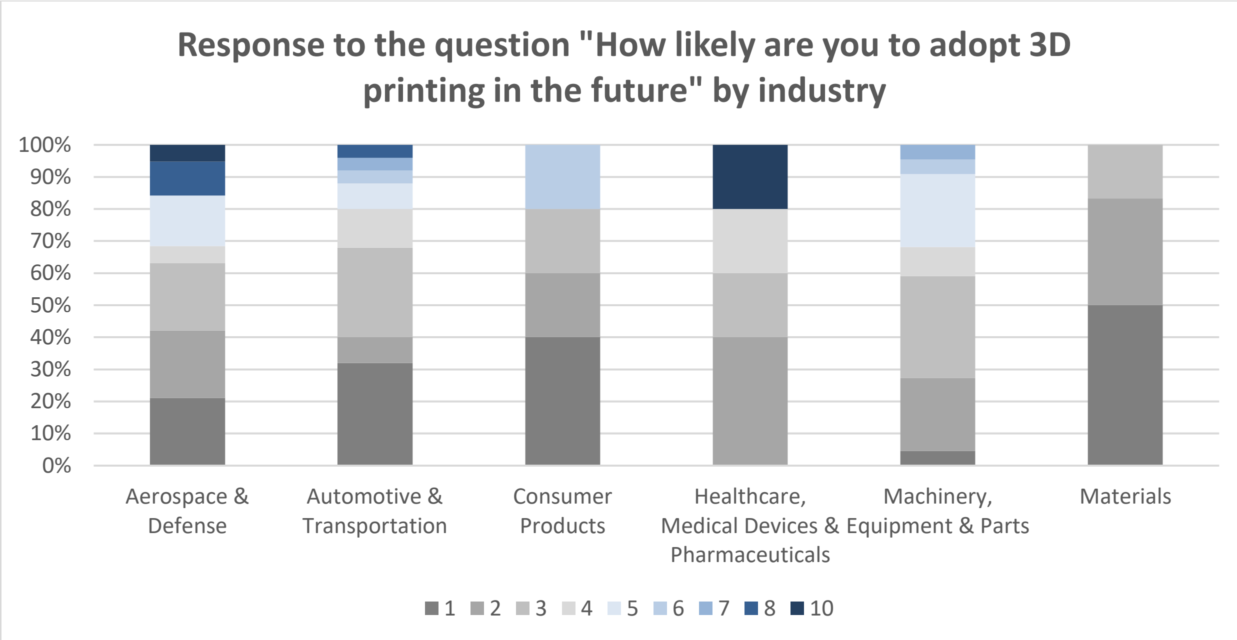

Figure 10 - Adoption likelihood segmented by industry

In terms of the application of the technology, most players indicated that the use of 3D printing will be primarily for prototyping purpose rather than mass production. However, Aerospace and Healthcare companies will use the technology for small batches and customized parts production (Figure 11). We don't see much potential usage of the technology for mass production purposes. This is due to the strong cost advantage that current process has in making large batch components.

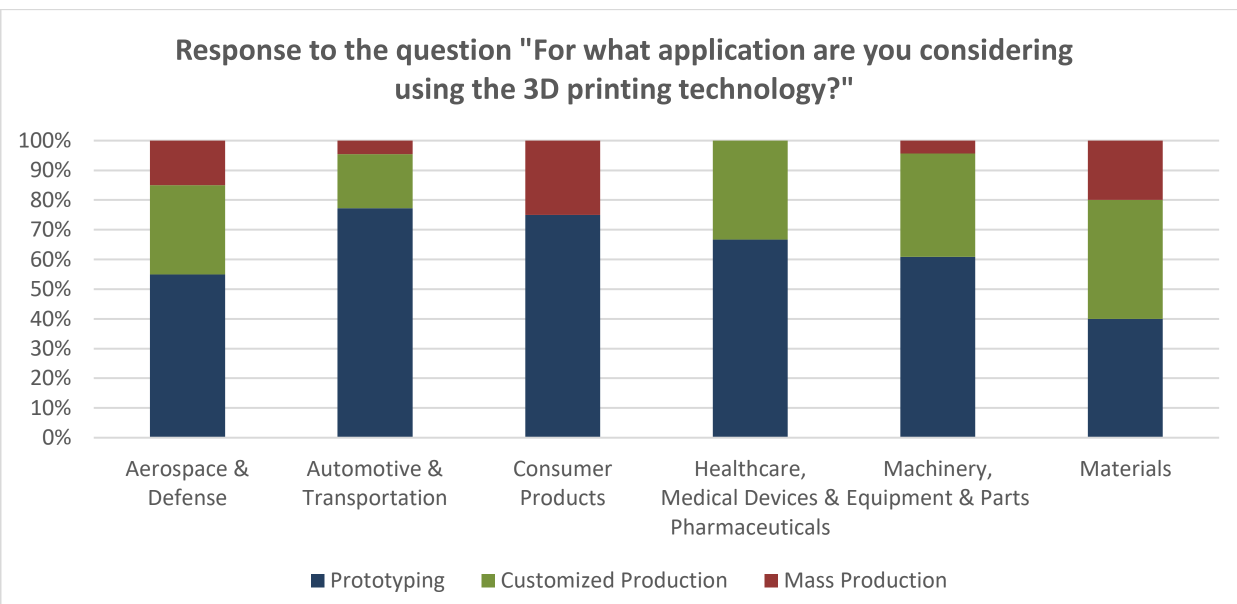

Figure 11 - Applications segmented by industry

With respect to the stages that the surveyed companies are currently in the adoption process, we see Automotive and Healthcare companies making big progress in this area compared to others, and some are currently testing and evaluating the effectiveness of the technology (see Figure 12).

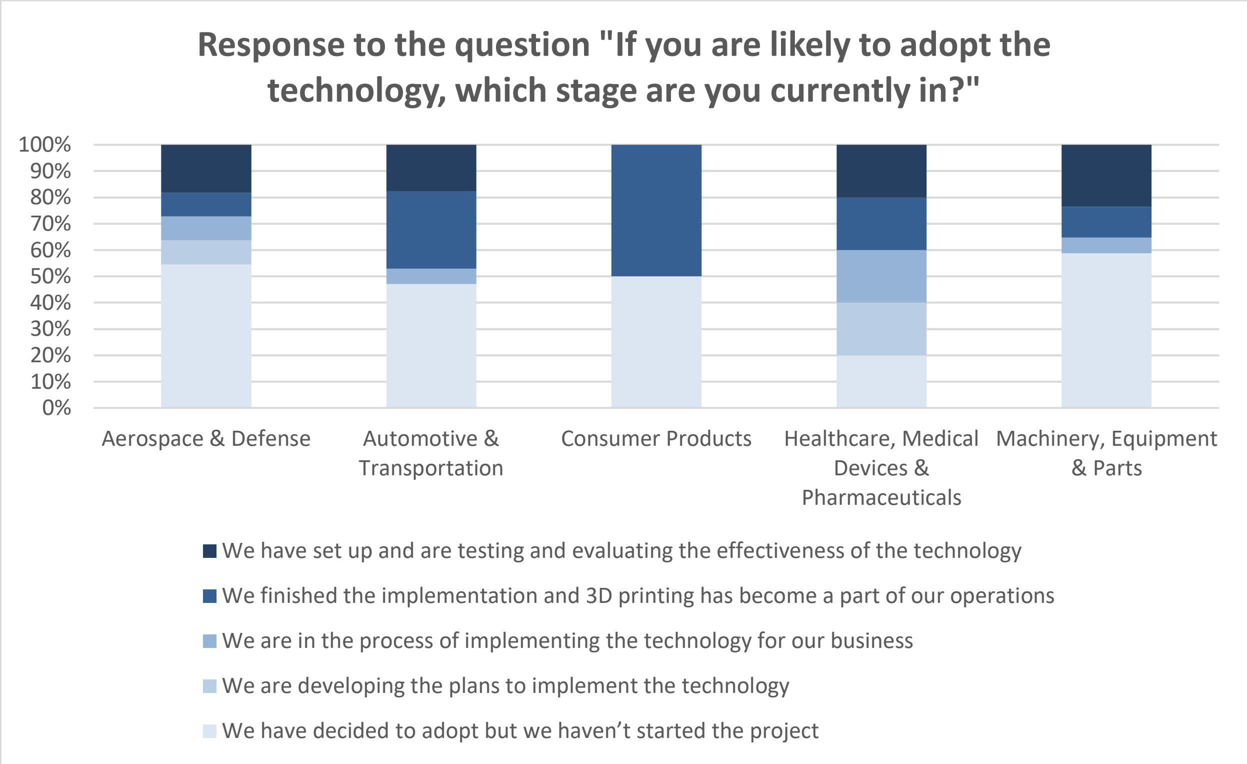

Figure 12 - Adoption stage segmented by industry

When looking at the responses to the question "How soon will you adopt the technology?", it seems that the adoption and implementation will happen and finish in the medium (3-5 years) to long term (5-10 years), as seen from Figure 13. This is in line with the previous responses that many companies are still in the process of developing the plan and implementing the technology. With the limitations of quality standards and materials that can be used, this change in manufacturing process is less likely to happen in the short term.

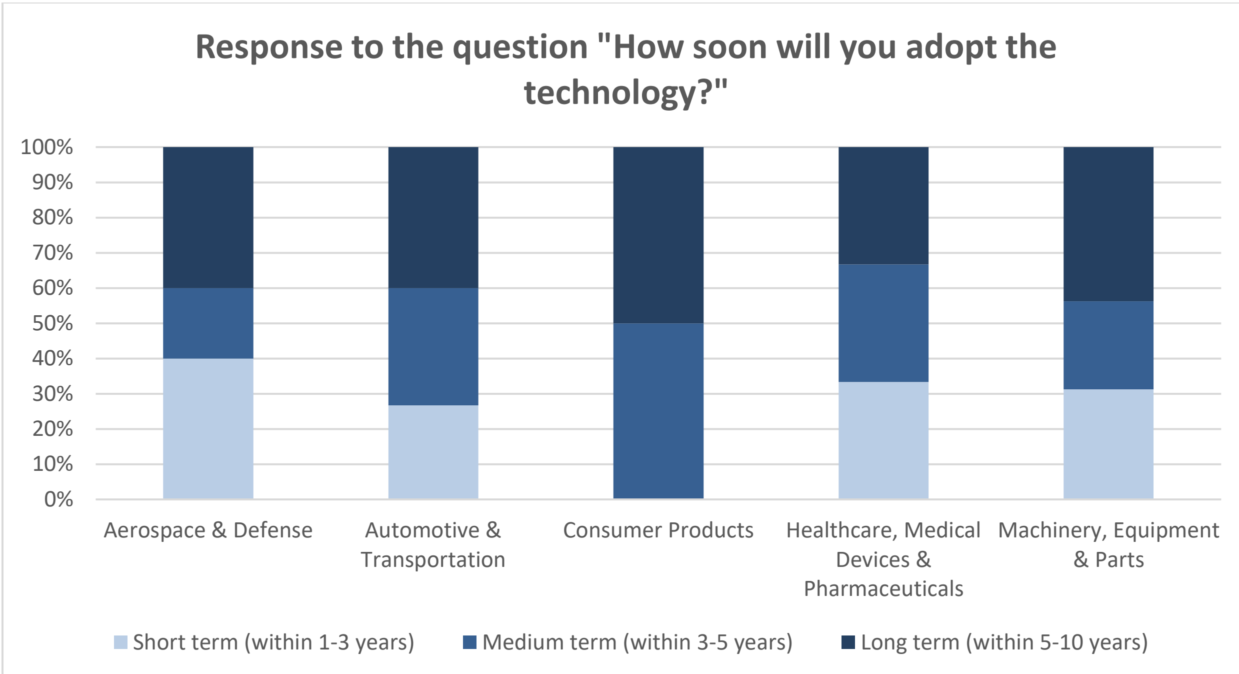

Figure 13 - Adoption timeframe segmented by industry

In terms of the benefits of the 3D printing technology, Figure 14 shows the key benefits segmented by industry, where the top four benefits of each industry are highlighted. According to the graph, Automotive and Aerospace industries value the cost reduction and lead time reduction more than other benefits, as mass production is the key element in manufacturing in these industries. Also design freedom and complexity reduction are important to these two industries, given the high quantity and complexity of components manufacturers typically include in the design. On the other hand, in Healthcare business we those companies value benefits of greater design freedom, lead time reduction and ability to customized products, given the high customization required in making medical parts. Machinery industry sees ability to customize parts and design freedom as the biggest benefits, given the customization nature of the industry as well.

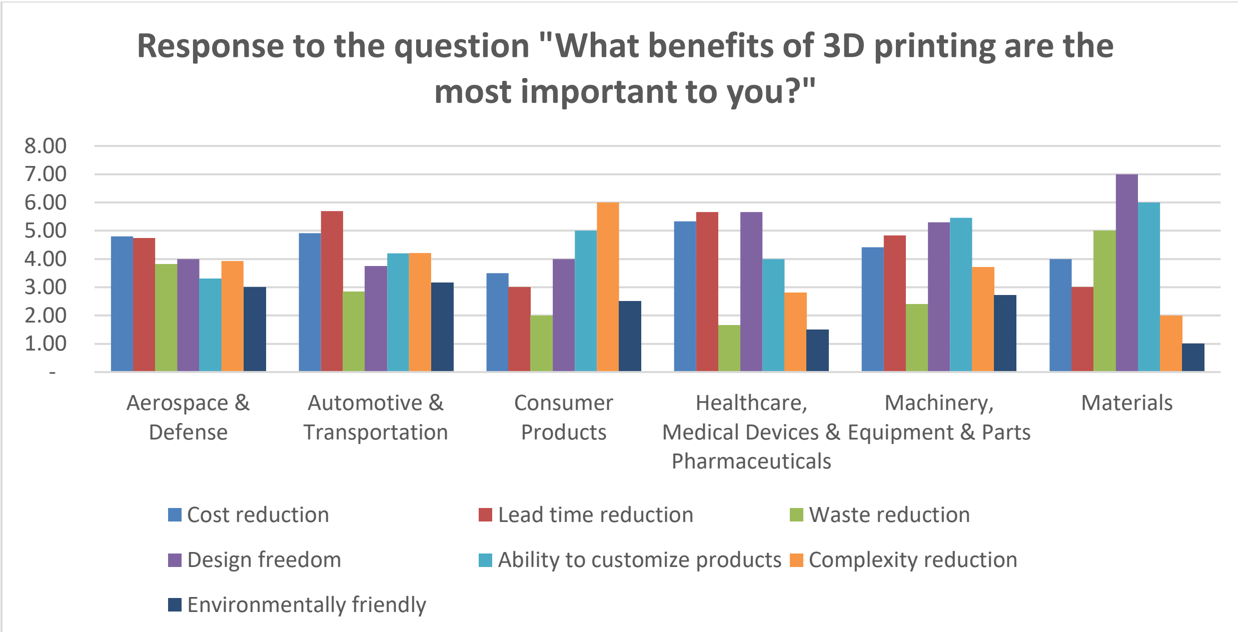

Figure 14 - Key benefits segmented by industry

Regarding the barriers to adoption of 3D printing, we see the different barriers among different industries, as seen from Figure 15. The biggest barriers in the automotive and aerospace industries are the limited type of materials available, given the need of diverse type of materials used in the automobiles and aircraft. In addition, the lack of standards is also an important issue as these industries require high precision to build components, and the current 3D printers have limitation in this area. In Healthcare business, the major barriers to adoption are higher capital investment and limited type of materials required.

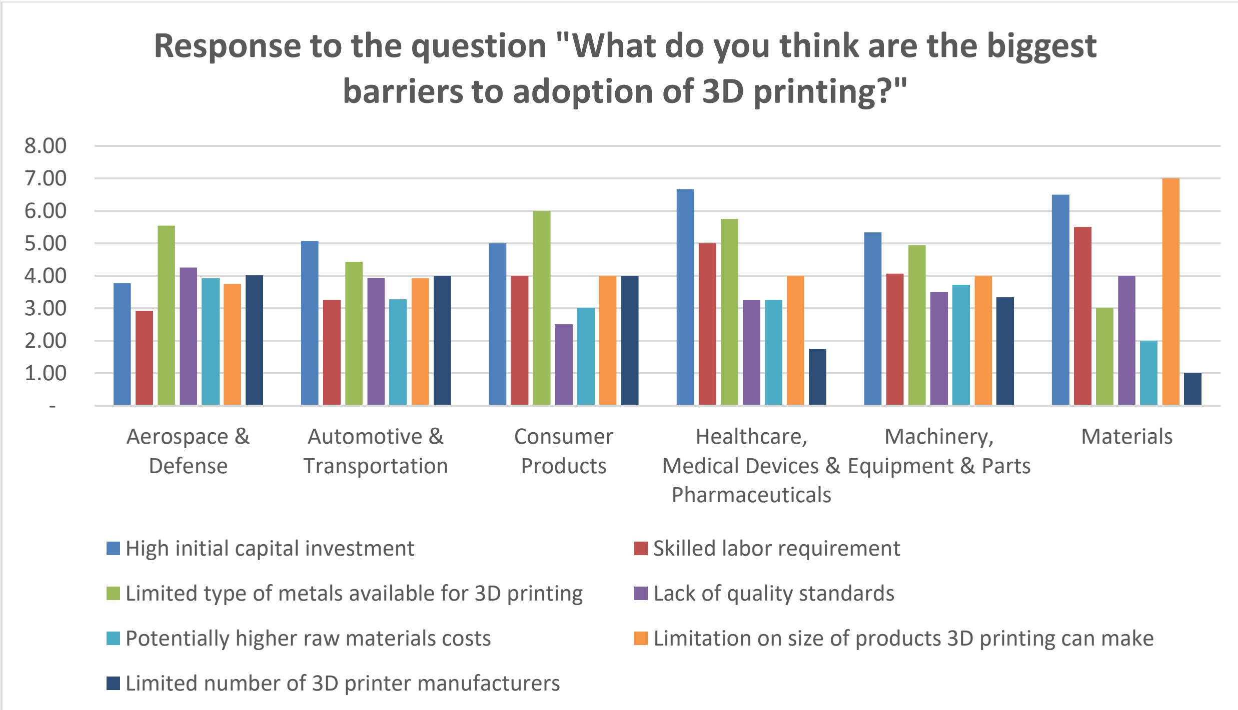

Figure 15 - Biggest barriers segmented by industry

5.4. Analysis of the results by company size

When we analyze the size of the companies that answered the survey, we notice that most of them are small (1-50 employees). Figure 16 shows how the respondents are segmented by size:

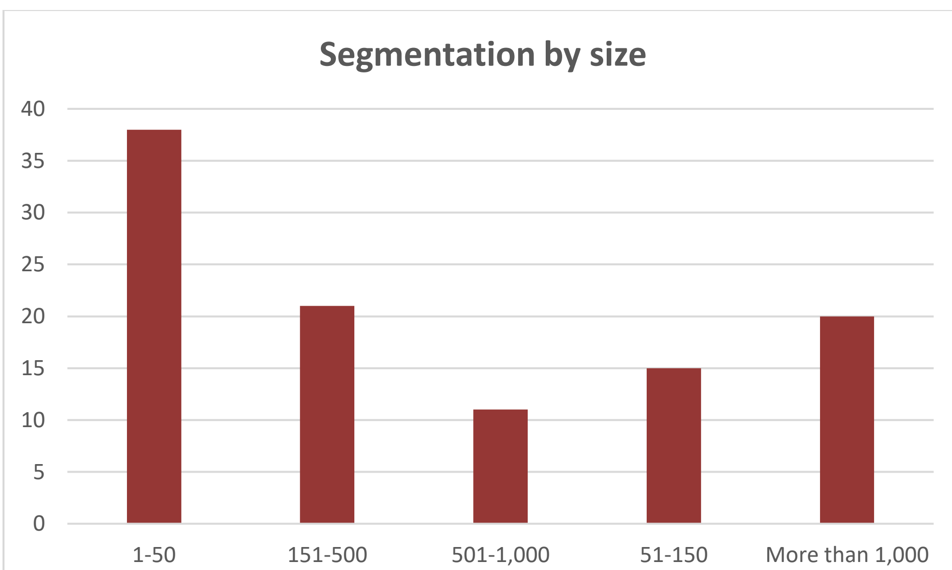

Figure 16 - Respondents segmentation by size

Regarding their familiarity with 3DP, most business are aware of the process (Figure 17), independent of their size. Two interesting patterns are revealed by this segmentation:

- Medium sized business (151-1,000) have the largest proportion of customers that are not aware of how AM works. At best, they have little knowledge about it.
- After large customers (more than 1,000 employees) the small shops (1-50) are the slice that is more aware of how AM works and have even adopted it. One hypothesis for this is that they are trying to differentiate themselves from the largest competition by adopting new technologies very early.

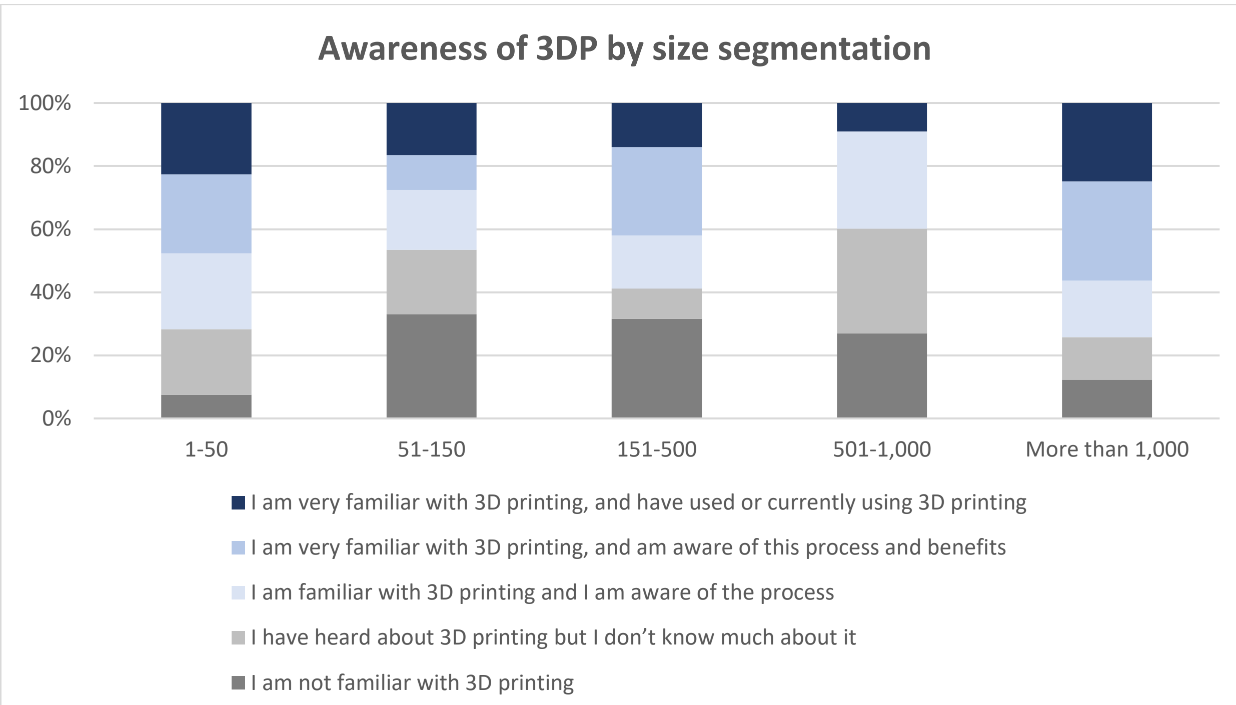

Figure 17 - Awareness of 3DP segmented by size

In Figure 18 we can see the adoption intention of 3D printing. The lower parts of the bars correspond to no intention to adopt. As we walk up the bar, the intention to adopt increases, with the dark blue being the intention to replace 100% of the manufacturing process with 3DP.

For large business, a surprising 29% of respondents say that, at some point, they are considering replacing 100% of the production process with AM. For small business, 9% says that too. Given the high initial investment cost, one possible explanation for this are businesses that were born dependent of 3DP. One example is a company that was visited for the project, that manufactures 3D printed prosthesis for hips and knees. Since the beginning, their process was 100% based on AM.

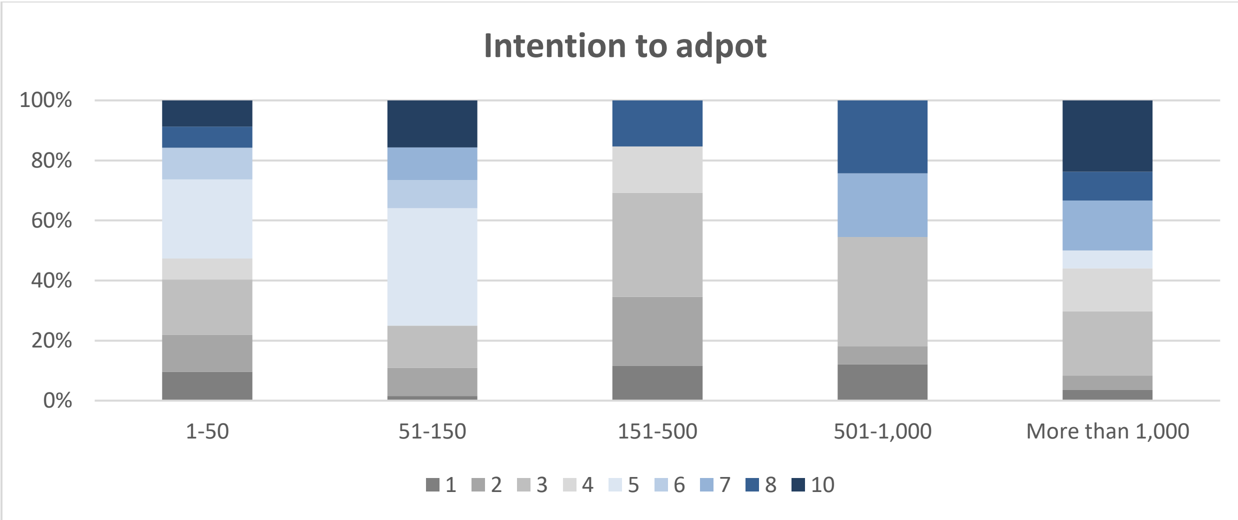

Figure 18 - Intention to adopt AM segmented by size

When asked about which stage on the implementation process they are (Figure 19), independently of size, most business says that they have decided to adopt AM but have not started the process yet. The second largest group says that they have finished the implementation and 3DP is already part of their operations.

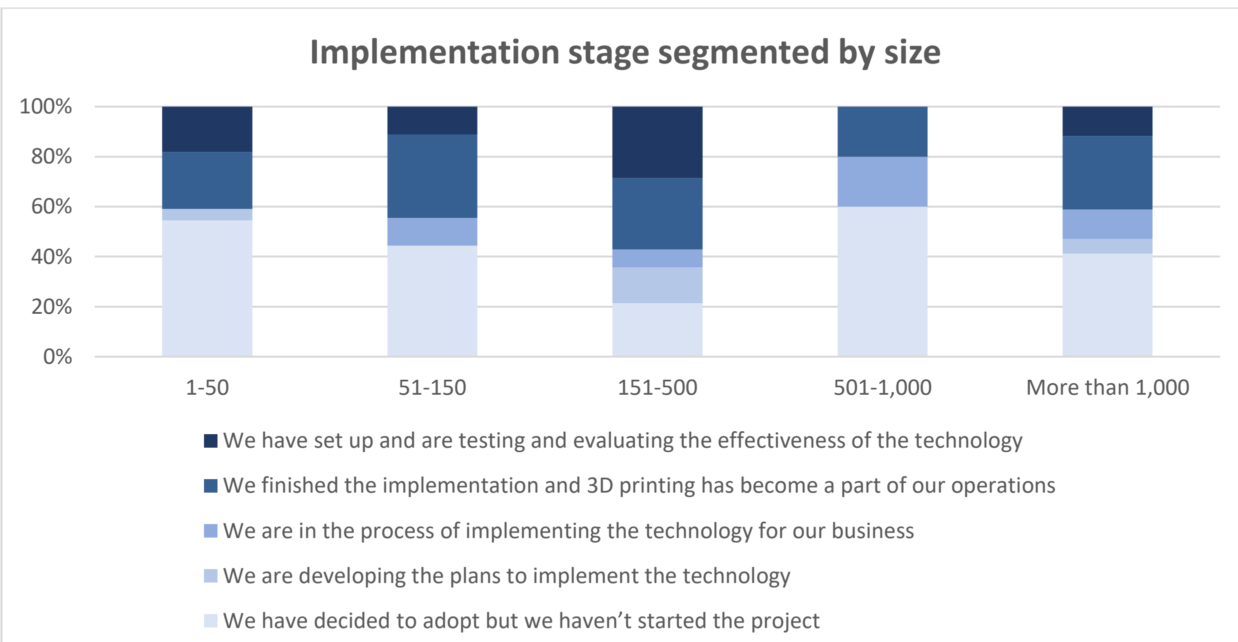

Figure 19 - Implementation stage segmented by business size

If we look at Figure 20 we notice that very large and very small business are the ones willing to adopt in the shorter time frame. This is very consistent with the answers given by them to the question of how aware of 3DP process they are. One interesting finding from this segmentation analysis is the fact that medium sized business (501-1,000 employees) say that they are considering adopting AM in the short term, but they are not very aware of the process. One possible explanation for this could be the fact that they know that to keep being competitive they have to adopt new technologies, but still have not started to look deeper into it.

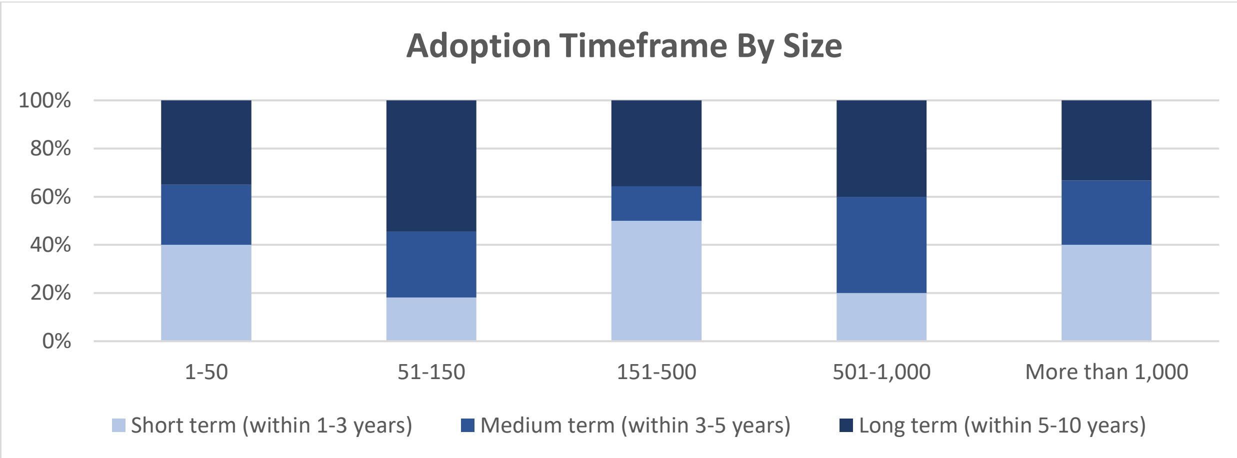

Figure 20 - Adoption timeframe segmented by size

In accordance with what is described in most of the literature, the main application business see for 3DP is for prototyping. As shown in Figure 21, independently of size, the main application for 3DP is prototyping, with some application to customized parts production specially for very small and very large business.

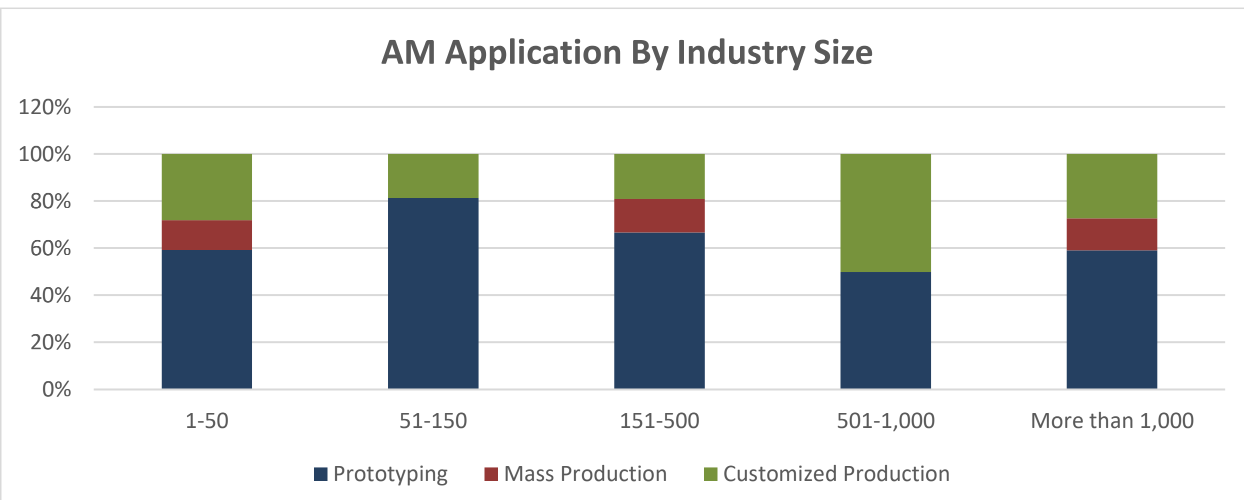

Figure 21 - Application segmented by size

The main benefits claimed to be the most interesting for all business, independent of their size, are cost reduction, lead time reduction and design freedom. This is very in line with the main application: prototyping. The business size does not have much impact on the benefits that more important, as shown by Figure 22.

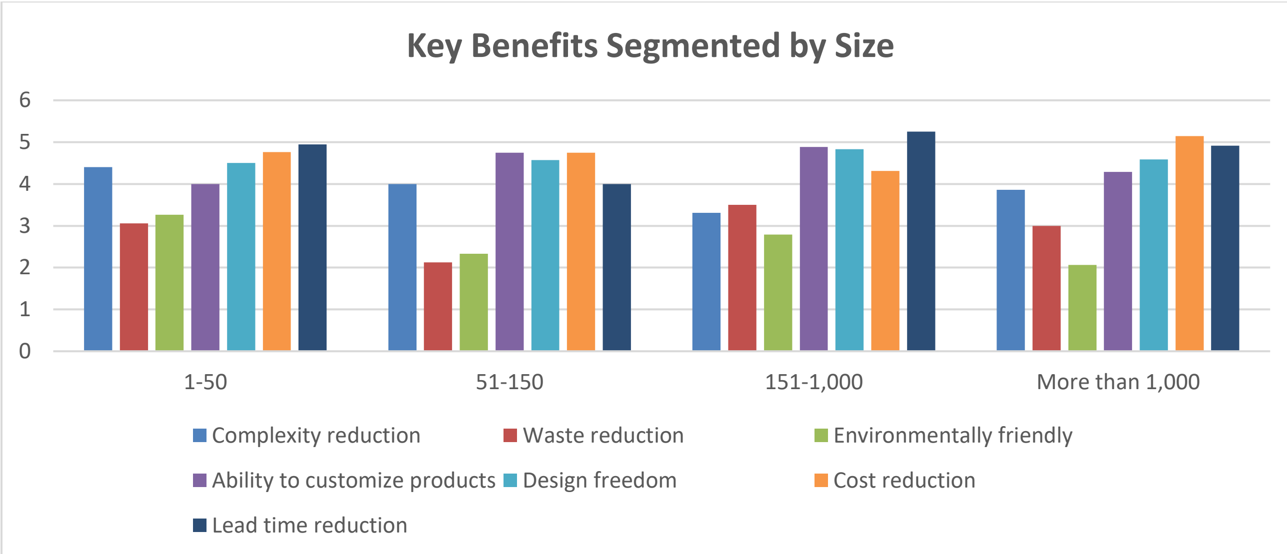

Figure 22 - Key Benefits segmented by size

The same applies to the main barriers (Figure 23): there is no big difference based on size segmentation. As one would expect, high initial capital investment is the biggest barrier. Surprisingly, it was considered a bigger barrier for very large firms than for very small firms. One explanation may be that many small businesses were "born" using 3DP, in contrast to large businesses, that have been established for a longer time and consequently started their operation before the advancement of AM.

The second major barrier is the limited diversity of raw materials, follow by the size limitation of what can be printed.

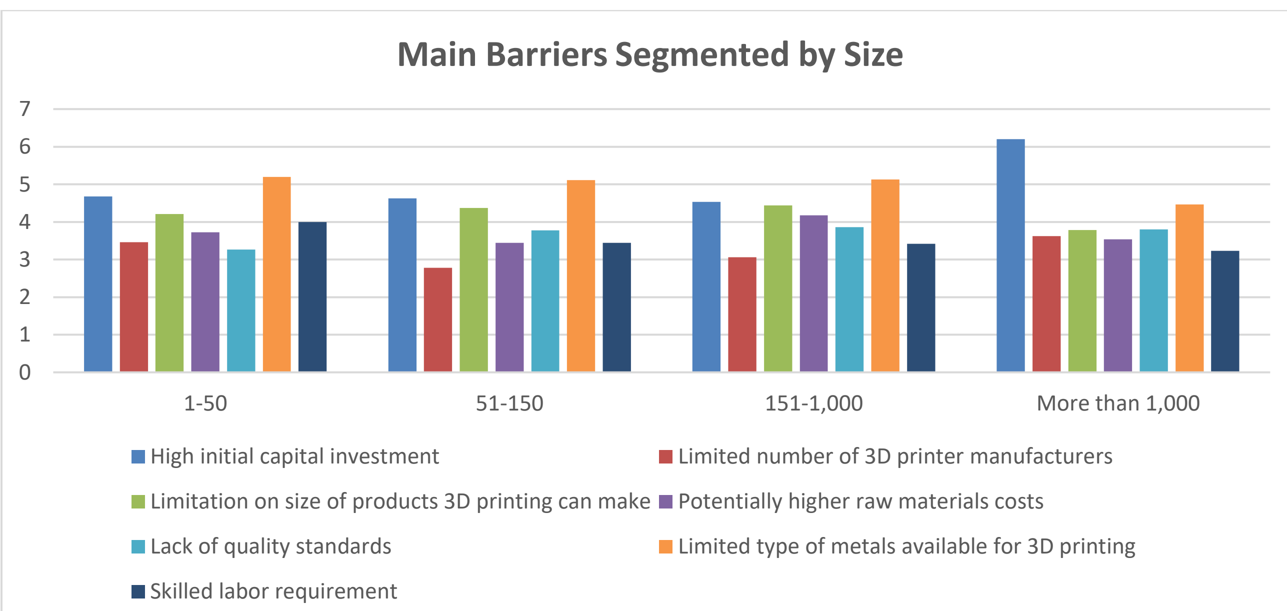

Figure 23 - Main Barriers segmented by size

6. Conclusion

3D printing is a promising emergent technology. Like most new technologies, 3D printing still needs to evolve before it can be widely adopted by the metal working industry. While it is already viewed as a viable and useful technology, AM still has barriers to overcome. Currently, the main barriers for most business are the high initial investment required and the limitation of materials available for 3DP. Limited printable size also is a main concern regarding AM adoption, independent of the industry segment and business size.

An interesting way to evaluate the adoption speed of AM is by comparing it with the adoption curve of some technologies that are now very common, as shown in Figure 24:

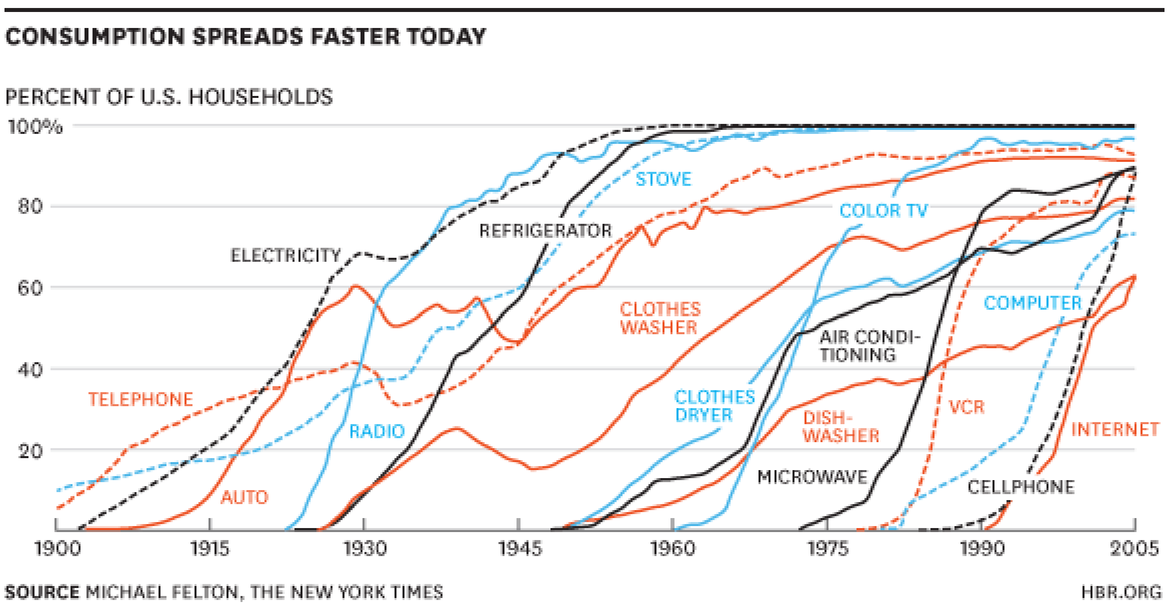

Figure 24 - New technologies adoption rate

The key benefits that businesses are expecting to gain by adopting 3DP are shorter lead time, cost reduction, and design freedom. These expectations are aligned with what was seen during site visits and calls. One interesting benefit of AM is the possibility to redesign a part, lowering the amount of raw material needed to produce it. This redesign leads to a new shape that would not be possible with traditional CNC. Unfortunately, these opportunities were beyond the initial scope of this project but may be an interesting topic for future research. Another interesting topic for future research could be why the small businesses are the most likely to adopt AM while cost is one of the main adoption barriers.

The present study points out that 3D printing tends to be used primarily for prototyping, even though it has more capabilities. This may indicate that there is a gap for better prototyping techniques in the metal working industry that has not yet been filled. While 3DP seems the most promising technique so far, new technologies may emerge for this purpose in the meantime. Another conclusion reached through this study is the potential areas in which AM could be used to manufacture the final product. Our research suggests that the main area in which 3DP could be used in this way would be medical devices, since this is an area where individuals are willing to pay a premium for 3D printed components. One example is the prosthesis industry, in which a AM part would fit exactly in the patient's body while the standard ones may lead to some discomfort for the rest of the patient's life.

In general, 3DP has been well accepted by different sectors of industry and its usage will likely increase fast in the next years. This research has pointed out the early adopting industries that are using it now, and enabled a better understanding of future trends.

7. Implications of the results for the sponsoring company

By using our customer prioritization framework combined with the potential adoption data from the survey, the sponsoring company may be able to identify target segments where they could focus their offerings of 3D printing products in addition to other industrial equipment products. In the framework, we prioritize customer segments based on two main criteria:

1. Attractiveness of the 3D Printing market within the segment: The attractiveness of

the 3D printing market within a segment is the potential size of 3D printing market within that particular segment in the medium to long term (5-10 years). We determine the attractiveness by multiplying the manufacturing revenue potential of each segment, with the 3D Printing adoption fraction data:

3D Printing market potential = Manufacturing revenue potential x 3D Printing adoption fraction

The manufacturing revenue potential is the total industrial equipment market size of that segment, in which we obtained the data from our sponsoring company. The 3D Printing adoption fraction is the percentage of the manufacturing line that will be replaced by 3D Printing technology in that segment, in which we obtained the average data from the survey question about the extent to which companies will adopt the 3D Printing technology, from the scale of 1-10. The scale is then converted to a percentage where we multiply that number with the manufacturing potential. For example, if the automotive industry has $1B manufacturing potential and the average response on the extent of 3D Printing adoption question is 3.5, we converted 3.5 to the adoption fraction of 0.35 and we get the 3D Printing potential of $350M.

2. Sponsor company's ability to compete within that segment: The sponsor company's

ability to compete within a segment is a measure of capabilities of the company to win in that segment. In this context, a high ability to win in a segment means that the company has established strong brands, distribution network, strong relationships with customers in that segment. This will allow the company to cross-sell or up-sell their products or services to customers in that segment. For example, if our sponsoring company has sold a lot of industrial equipment to aerospace manufacturing companies and has established strong presence in this segment, the company can leverage their existing relationships and salesforce to offer 3D Printing products to those customers. However, there is a challenge in obtaining data related to organization capabilities, so we use the sponsoring company's market share within the segment as a proxy. We believe there is a high correlation between market share and capability of our sponsor in service customers in that segment.

The customer segments where the attractiveness and the ability to compete is high will be prioritized. This means our sponsoring company should go after those customer segments first, followed by segments with lower attractiveness and ability to compete.

After we obtained the data and run the analysis, we obtained the following results:

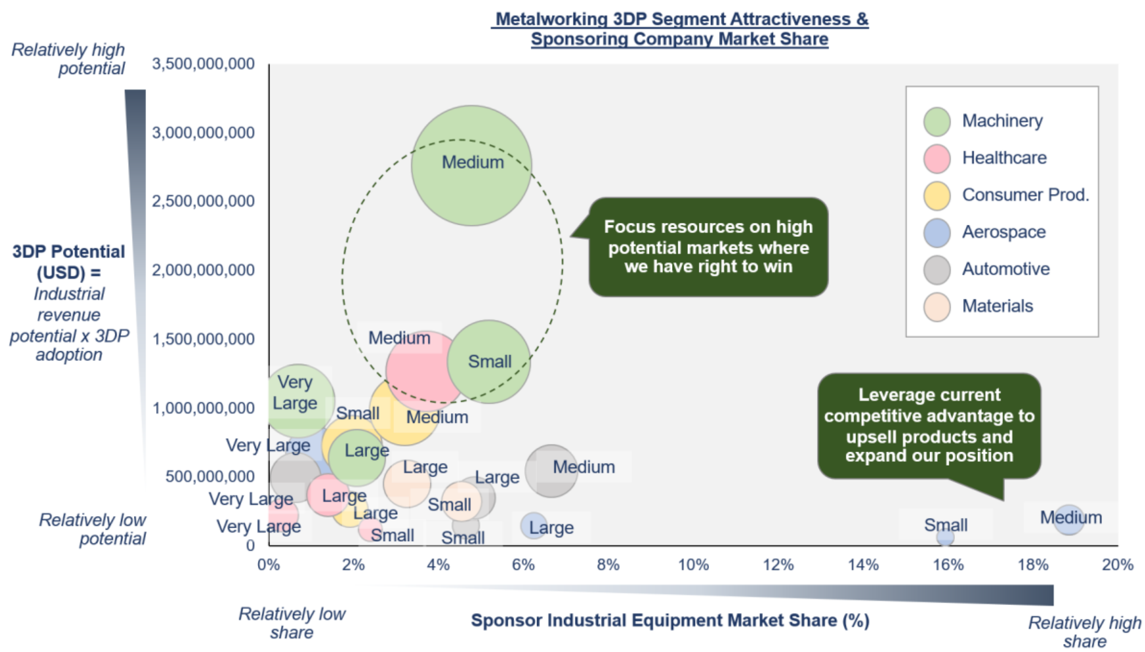

Figure 25 – 3D Printing customer segment prioritization

According to Figure 25 small and medium machinery manufacturing companies, and medium healthcare manufacturing companies are the ones our sponsoring company should prioritize. This is because the machinery manufacturing industry has a relatively large manufacturing revenue potential, and the 3D Printing adoption potential data we obtained from the survey is also higher than others. We can also see from the Results section that machinery companies could realize great benefits from 3D Printing in terms of ability to customize parts and design freedom, in addition to lower cost and faster lead time, since this industry seems to make more customized parts than automotive and aerospace industries. Also, small and medium companies have higher attractiveness and potential for our sponsor to compete, as the machinery manufacturing industry is relatively fragmented in that small and medium sized companies make up a large share of revenue potential. Moreover, our sponsoring company has relatively good amount of market share within this segment. These make the segment high priority. Medium-size healthcare companies are also relatively attractive and our sponsoring company has a good market share. These are the companies that make customize medical parts, and 3D Printing could offer the benefits of design freedom, lower lead time, and customization. For other segments further down, once our sponsoring company has gained market share in the prioritized segments, they can move down the chart to these less attractive ones.

According to Figure 25, small and medium aerospace manufacturing companies are also the ones our sponsoring company could focus, as it has relatively high market share within those segments. If the company is already established a strong foothold and have reach a mature stage where it is harder to increase their wallet share. New 3D Printing products could be the opportunity to expand in those markets and maintain strong presence.

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