

**Additive Manufacturing Technologies' Sustainability Contributions in the
Aerospace and Medical Industries**

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Abstract

Developments in the Additive Manufacturing(AM) technology have started to shape the manufacturing industry. With further AM integration into production models, further study is needed to study the implications of this integration. Sustainability outcomes of such integration have not yet been widely studied. Therefore, we have identified a number of issues to address. In this thesis, we looked upon economical, environmental and social dimensions of sustainability with AM integration in the aerospace and medical industries. We looked upon the level of disruption AM brought towards business models, decentralized production and supply chains with respect to disruptive innovation theory. Additionally, we studied recent developments of AM technologies in the aerospace and medical industries. We have found out that AM adoption resulted in a number of economical, environmental and social benefits; as well as a number of challenges for both the technology and sustainability.

Keywords: additive manufacturing, 3D printing, 3d printers, sustainability, economical sustainability, environmental sustainability, social sustainability, aerospace, medical, biomedical, aerospace industry, medical industry, disruptive innovation, decentralization

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List of Abbreviations

3D: Three-Dimensional

3DP: Three-Dimensional Printing

3DPI: 3D Printing Industry Website

3DS: 3D Systems Company

ACS: American Chemical Society

AM: Additive Manufacturing

CAD: Computer Aided Design

CAM: Computer Aided Manufacturing

CNC: Computer Numerical Control

CSAIL: Computer Science and Artificial Intelligence Laboratory

CT: Computerized Tomography

DDM: Direct Digital Manufacturing

DLP: Digital Light Processing

DMLS: Direct Metal Laser Sintering

EBAM: Electron Beam Additive Manufacturing

EBM: Electron Beam Melting

FDA: United States Food and Drug Administration

FDM: Fused Deposition Modeling

GE: General Electric

GRI: Global Reporting Initiative

IP: Intellectual Property

LOM: Laminated Object Manufacturing

MIT: Massachusetts Institute of Technology

MRI: Magnetic Resonance Imaging

MQB: Modularer Querbaukasten

NUS: National University of Singapore

PBF: Powder Based Fusion

PERFORMANCE: Personalized Food for the Nutrition of Elderly Consumers

R&D: Research & Development

SDL: Selective Deposition Lamination

SLA: Stereolithography

SLS: Selective Laser Sintering

SME: Small and Medium Enterprises

THOR: Testing High-Tech Objectives in Reality

TPES: Total Primary Energy Supply

UCLA: University of California at Los Angeles

1. INTRODUCTION

1.1 Research Background

Additive Manufacturing (AM) —also commonly referred as three-dimensional printing(3DP)— is a method of production that uses additive ways of manufacturing compared to the traditional subtractive manufacturing methods. In AM, products are built layers upon layers to form a product by spraying or melting different materials into a layer. With important breakthroughs mainly in the 3DP technology through the last decade, hype towards 3DP is on the rise. With many new products being introduced to consumer markets and industrial markets, constant improvements of the technology and expectations towards a revolutionary change it will bring; many questions arise in terms of how disruptive and how sustainable this new technology will be. AM technologies are not new. Since the late 1980s, AM has been used by different industries for different purposes. With constant improvements of the technology, many more industries and fields also started to use AM in their manufacturing practices. As AM capabilities constantly increased, a question arises on “how did AM and 3DP managed to draw this much attention from the media, the academia and the industry?”. In order to understand and cover such questions, there is an immediate need of research to understand capabilities, advantages and challenges of AM. In our thesis, we are going to conduct an explorative research to address a number of questions. *Firstly*, we will be looking at developmental phases of AM since its discovery until today. *Secondly*, we will research recent developments of AM in the aerospace and medical industries since these industries have already started to adopt AM at greater levels compared to other sectors and innovation trends in these sectors are better aligned with developments in the AM technology. *Thirdly*, we will be looking at the businesses in terms of their reaction and adoption of AM technologies and their effect towards business models. *Fourthly*, we will try to answer the question whether AM is a disruptive innovation and/or a sustaining innovation. Finally, we will be addressing sustainability concerns of AM adoption by looking at economical, environmental and social dimensions of sustainability. All of our five steps were the reason for our review of the current literature and industry reports, thus detecting missing linkages of information. Overall aims of this research are to explore sustainability implications of AM in terms of economical, environmental and social dimensions of sustainability. Thus, this research was designed accordingly, as explained in the following part of this section. It is important to underline that the technology is relatively new and academic research is limited at the moment. Therefore, this research is an explorative one as mentioned. Thus, there might be errors on the long run. However, the aim of this research is to shed a light on the path of AM in terms of its disruptiveness and sustainability contributions.

The motivation for this research derives from the lack of previous research towards “an established view towards AM” in general public and industry. In order to understand developments in AM, a systematic and academic research is required. So far the current literature only covered broad aspects of AM in line with trends in the industry, public and academia. In terms of sustainability linkage of the AM, there have been exemplary researches conducted by Gebler et. al (2014) and Ford and Despiesse (2016). These researches stated that there is a need for sector-specific studies in terms of AM and sustainability. Additionally, conclusions reached by these researchers indicate that there is also a lack of sector-specific data to conduct comprehensive researches. This lack of data also effected the quality of our research since it is very hard to acquire empirical data to look at AM and sustainability linkages quantitatively. Thus, this led to our research being a qualitative one with comparably small amounts quantitative data that was acquired from the current literature and industry-leading companies. However, this data is not comprehensive enough to make this research a quantitative-driven one. It must also be stated that acquirement of an empirical quantitative data is not available due to given time constrains and scarcity of resources allocated for this research.

Deriving from our findings in the current literature, a few missing points have been detected in terms of AM effects towards the broader levels of the industries. These are mostly on the capabilities of AM to change/shape the industrial landscape as people started to refer AM/3DP as Industry Revolution 3.0/4.0. In order to acknowledge such revolutionary claims, there is a need for evidence. This leads to the hypothetical disruptive nature of AM. In this research, we have used a customized framework in order to understand disruptive nature of AM and answer the question “whether AM innovation is disruptive or sustaining”. In order to enrich our findings, two specific industries, namely, aerospace industry and medical industry was chosen. The reason behind choosing these industries as we mentioned above, is their early adoption of AM and the current momentum of innovation and development in these sectors towards AM utilization and development. We have looked at the reasons why these industries have decided to use AM technologies and how AM also transformed these industries in terms of production, customization, resource efficiency and design flexibility. For that section, we have studied the recent developments in aerospace and medical industries regarding AM evolution. This has given us a look at disruptiveness of AM at a glance. This research does not compare the two industries due to sectoral differences and the differences between results acquired from each industry. A brief

comparison was made during the Disruptive Innovation Framework but that was to make the different disruptive/sustaining effects more clear. After covering industrial developments, we have studied the AM adoption's effects on businesses. For that, we focused on indicators such as business model changes, supply chains' transformation around AM and social effects of such adoption and transformation. These indicators are giving us enough information to broadly conclude the disruptiveness of AM. Afterwards, we built our findings around our framework we have mentioned in Section 3. Results reached regarding whether AM is a disruptive innovation or a sustainable innovation. After we reached our conclusion, we moved towards the sustainability impacts of AM adoption. We have studied both current sustainability impacts of AM and hypothetical future implications. In order to enrich the future implications, we built a brief explorative scenario in light of our findings with the aim of shading a light towards AM technologies' contributions towards economical, environmental and social sustainability dimensions.

1.2 Research Questions

Taking these factors into consideration, we have developed one research question with three sub-questions to guide our research. Our sub-questions are designed to contribute to the main research question by focusing on related fields that are complementary in terms of our sustainability-based research. With our findings regarding sector-specific research, business-specific research and their interactions; overall aim is to reach to a comprehensively scientific yet explorative results in terms of AM and sustainability.

Our main research question is:

"Does AM contribute to sustainability in terms of economical, environmental and social dimensions of sustainability in the aerospace and medical industries?"

Our sub-questions are:

"Is additive manufacturing disrupting the aerospace industry and the medical industry?"

"What are the possible contributions of additive manufacturing towards sustainability?"

"What are potential future sustainability contributions and general challenges ahead of additive manufacturing?"

Even though we have mentioned that we will be looking also at social dimension of sustainability, our main focus is towards the economical and environmental dimensions of sustainability due to our limitations in terms of resources and time. Since current literature also focuses on economical and environmental dimensions, our findings will consist these two dimensions. However, we have gathered useful data to discuss expected social implications of AM in terms of sustainability. This data provides insights especially for the medical industry since in terms of the social dimension of sustainability, the medical sector is far ahead in terms of the amount of data we have acquired for the aerospace industry.

2. HISTORY OF ADDITIVE MANUFACTURING

Since the early 1990s, the term 3DP has been widely used to refer to an additive manufacturing method that comes with its own properties such as selective laser sintering (SLS), stereolithography (SLA) and powder based fusion (PBF). Even though some scholars discuss the differences and similarities between 3DP and AM, some refer to 3DP as a different method than AM, while some state that AM and 3DP fall into same category (Schniederjans, 2017; Rayna and Struikova, 2016; Barz et al., 2016; Gross et al., 2014; Ford and Despiesse, 2016; Gebler et al., 2014). Regardless of the discussion on whether two are different or similar, the main point is that with the AM and 3DP technologies; we have seen a new dimension of manufacturing deriving from AM technologies. In this research, we are defining 3DP as a part of AM since their properties match. Bassett et al. (2015) mentioned that AM stands in contrast to conventional subtractive manufacturing processes by adding layers upon layers in order to form a structure, unlike conventional methods such as CNC, CAM, laser and water jet cutting techniques. 3DP is also an AM method that uses the same principle as AM that prints materials layers upon layers in order to reach to the final product. Therefore, we acknowledge 3DP as a method for AM technologies. Bassett et al. (2015) also added that with AM, 3D shapes can be created such as certain hollow and shell components, of which were not possible with traditional subtractive methods. First examples of AM can be traced back to 1980s. First of AM and 3DP technologies emerged in the late 1980s with the invention of SLA by Charles Hull. Crawford (2011) stated that the emergence of 3D printers started in 1984 by Charles Hull and Massachusetts Institute of Technology. Charles Hull later on founded the company 3D Systems in 1986 and became the first company in the market using 3D printers. Crawford (2011) details the technology used by 3D Systems such as SLA and SLS. These were the first methods for 3DP but later on, were followed by more advanced technologies and more companies to join the market. Other popular 3DP methods are fused deposition modeling (FDM), multijet/polyjet, digital light processing (DLP), direct metal laser sintering (DMLS), selective deposition lamination (SDL), binder jetting, electron beam melting (EBM) and laminated object manufacturing (LOM). According to 3D Printing Industry (3DPI) website (n.d.), earliest 3DP technology emerged in the late 1980s, however, there was a patent application filed by Japanese Dr. Kodama in 1980. Dr. Kodama failed to meet the deadline for full patent specification and lost the chance to be recognized as the inventor of the technology. First patent application for SLS system was filed by Carl Deckard from the University of Texas. These small initiatives were followed by other inventors across the United States and continental Europe. However, first commercial operations were

started in the late 1990s. 3DPI(n.d.) indicates that 1990s and 2000s were the years the technology started to take shape. With various methods of 3DP emerging, costs of those systems were expensive and the production never went beyond prototyping. 3DPI(n.d.) adds here that in 2007, the market has seen the first system at the price tag under USD 10.000 by 3DS. This might be seen as a breaking point because since then, prices have dropped significantly and 3D printers started to appear not just in the industry, but also in households for personal usage. Table 1.1 shows the current usage of 3DP methods in percentages. We are seeing a wide adoption of SLS technology followed by FDM and SLA methods. Other 3DP methods are also widely used by different sectors but their share is relatively smaller compared to the top 3 methods.

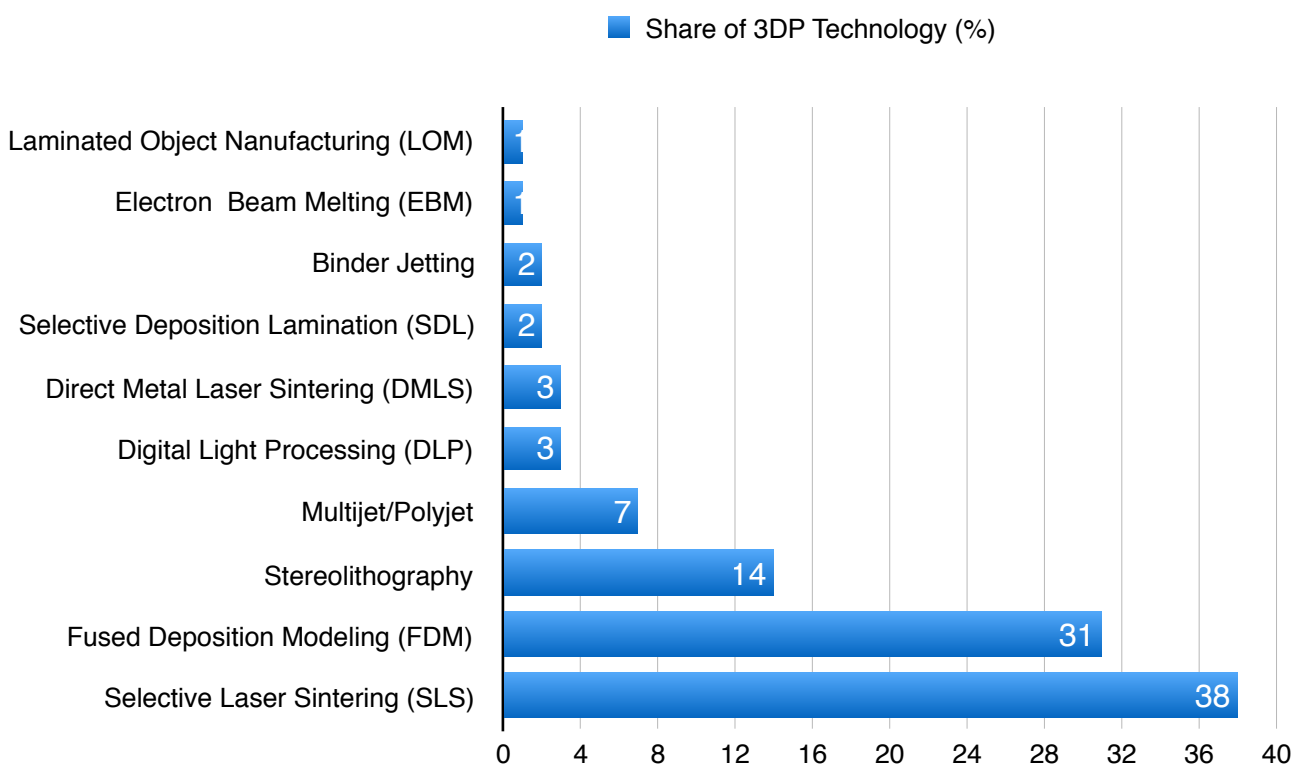


Table 1.1: Preferred 3D printing technologies. Source: Forbes, Statista

The Economist (2012) stated that the future of manufacturing will be an additive manufacturing, rather than conventional subtractive manufacturing while mentioning “third industrial revolution”. Referring back to the conventional methods of manufacturing as “desirable in terms of economies of scale”, The Economist (2012) underlines that with 3DP, the economies of scale would be irrelevant. Due to digitalization of the design and production, production is not limited to casts and molds. Thus, 3D printing offers flexibility and design freedom that many manufacturers are attracted to. Since its first introduction to the market, 3DP has

found many industries to emerge and develop. Automotive and Aerospace Industries were one of the first ones to use the technology for fast prototyping and also medical sector used 3D printers since the early 2000s for dental implants and prosthetics (Gross et al., 2014). Even though the 3DP has seen a rapid utilization in those industries, there were obstacles ahead of 3DP proliferation due to technical capabilities of 3D printers and AM. Since AM technology's invention back in the 1980s, there has been a little development towards the capabilities of 3D printers in terms of material usage, production speed and energy efficiency until mid-2000s. These factors have been a drawback for the technology to find itself wider scales of application in other industries. Due to these limitations, utilization of the technology was relatively limited to rapid prototyping, tooling and product design at the initial usages of 3DP. However, with the constant momentum of innovation in AM, 3D printers have also seen a range of developments that led to faster and more capable printers. Most of the AM practices focus on single-material builds. 3D printing is a fast and cost-efficient technique for creating complex products with mostly a single material. But in order to make the technology more feasible for wide-scale industry applications, multi-material printing with the reduced necessity to assemble different parts and decreasing faulty products that require the manufacturer to "start over the 3DP process" are required. MIT has announced in 2015 that they have developed a new 3D printer with the capability to print using 10 materials at once without needing to assemble finished parts. This new printer overcomes problems of traditional AM and 3DP machines by 3D scanning each layer during the production, thus eliminating the necessity for human interference in case of a misprinting. Therefore, saving time, costs and material usage. With this newly created MultiFab machine, printing resolution has reached to 40 microns —half the size of a single human hair— offering high-resolution printing with better-looking end-products. With this new technique, traditional 3D printing problems such as low-resolution, printing errors, material limitations and operator involvement would be solved (MIT CSAIL, 2015). Rayna and Striukova (2015) mentioned a new 3D printer with the capability of using 100 different materials and 14 materials simultaneously with the price tag of US\$ 250.000. Orcutt (2016) from MIT Technology Review highlighted a new innovation for 3D printers using metal powder. With this new additive manufacturing technique, 3D printed parts are now available to be built using multiple materials. According to Orcutt, Boston-based NVBOTS has developed a new 3D printing technique with the ability to use 21 different metals with a much cheaper and efficient method than current AM techniques. This new method uses electricity to melt metal wires to make it printable with AM methods, compared to the traditional usage of lasers and electron beams to

melt metals. With electricity-based melting, production costs would be much cheaper and energy efficient. With this method, conventional methods like casting would be challenged since small parts consisting titanium and stainless steel would be easier, cheaper and quicker to produce with better structural integrity and heat resistance.

The Economist (2011) stated that 3D printers are suitable for high-value and low-volume products. As of 2011, technology was considerably immature while multi-material printing and mass-production capability were not present. However, considering the fact that innovation trends in AM are making such capabilities a reality as of 2017, and these developments towards AM is expected to introduce better products into the market. Therefore, these developments are encouraging companies to further invest in AM technologies. As of 2017, development momentum of AM is expected to continue as technology finds itself more industries to emerge and more tasks to complete. The Economist (2012) mentioned that conventional production equipments are evolving and getting smarter. The example given is the Modularer Querbaukasten (MQB) developed by Volkswagen that allows the company to produce all of its cars on the same production line. This development is currently more attractive for car manufacturers since the transition from conventional manufacturing to additive manufacturing requires fundamental changes in their business models and factory designs. In order to catch the pace and close the gap, AM also needs to be improved to increase its competitiveness and attraction compared to conventional methods. It is also noteworthy to mention that with the increased automation of the conventional production methods, large factories filled with workers are becoming more obsolete day by day. Current levels of AM still require human interference but recent developments such as multi-material printing and mass-production capability are signaling that AM will be competing for the title of the key manufacturing method for the future of manufacturing. Currently, AM offers very limited human interference during the production, thus making it more desirable than conventional methods in terms of automation demands by manufacturers.

According to Strataysys, global AM industry accounted for US\$ 5.17 billion in 2015. As of 2017, global AM industry accounts for more than US\$ 7 billion. The rise of AM industry can be seen at Table 1.2 presented below. Expectations indicate that the global AM industry will be reaching to US\$ 12.5 billion by 2018. According to Wohler Associates, global industry has reached to 25.9% growth rate in 2015 compared to 2014. The increase of this growth rate is expected to rise for the upcoming years as

more industries starts to adopt AM with increasing attractiveness of AM technologies due to constant improvements and developments.

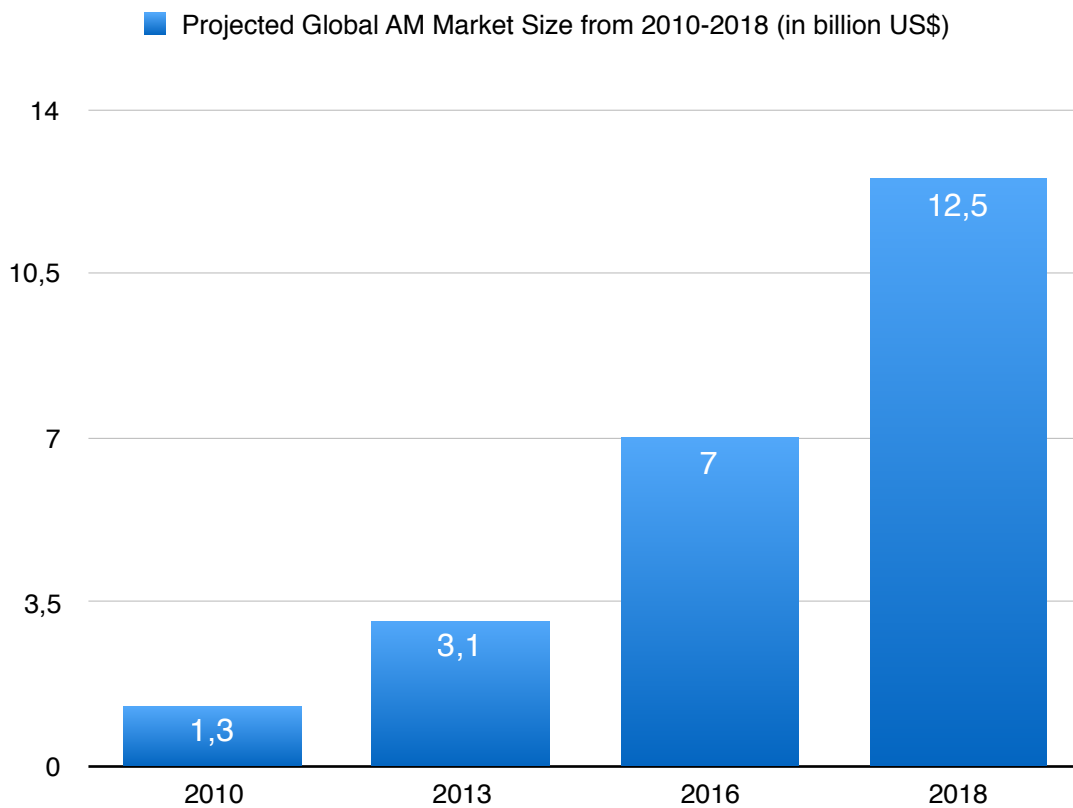


Table 1.2: Projected global AM market size from 2010 to 2018. Source: consultancy.uk, Statista

3DP is mostly used for rapid prototyping since its emergence as a branch of AM back in the 1980s. Due to the limitations of printers such as overall quality, material usage, size limitations and production speed; manufacturing end-products at a larger scale were not feasible until mid-2000s. With the developments of AM and 3DP technologies, more applications of the technology were made possible. Currently, AM is used for the production of tools, consumer goods, high-value products, functional components, aircraft components, medical products and even alive tissues. The Economist (2011) stated that as of 2011, 20% output of 3D-printed products are final products rather than prototypes. Terry Wohlers is owning a research company (Wohlers Associates) that specializes in the field has told The Economist that he expects a rise from 20% to 50% by 2020 in terms of final products. Table 1.3 below mentions the current usage of 3DP for the years 2015 and 2016. Compared to the previous levels, we have seen an increase in the manufacturing of final products and educational uses. Even though Schneiderjans (2017) stated that 3DP usages indicate 67% for prototyping and 10% for final product manufacturing, recent data obtained

from Forbes and Statista suggest different numbers in terms of final product manufacturing. We must also state that the data shown below does not specify the “production” part as for final products or also parts and product components. Given the fact that data only suggest 53% prototyping usage for 3DP, we are observing a distributed pattern regarding the distribution of 3DP usages. However, we present more optimistic numbers since our findings suggested that we will be seeing increasing usages of AM for final products. The yellow bar indicates different and independent projections by professionals in the industry and the academia. Thus, the numbers are different than the blue and green bars. The yellow bar allows us to understand the given level of attention towards the leading uses of 3DP by the professionals in the year 2016. Blue and green bars are the adjusted results for the given years.

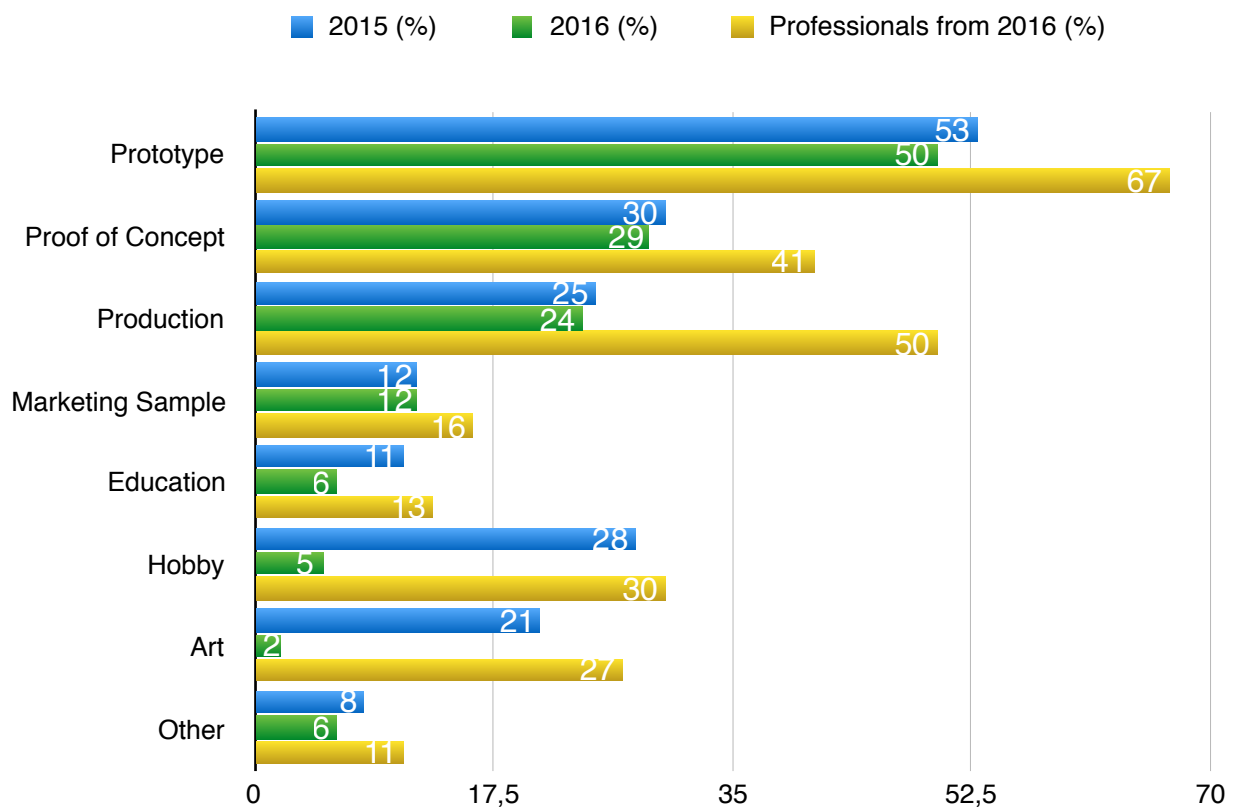


Table 1.3: Leading uses of 3DP in 2015 and 2016. Sources: Forbes, Statista

3. METHODOLOGY

In order to understand sustainability contributions of AM, we have looked at specific dimensions of sustainability. Widely known three pillars of sustainable development were selected as our focusing points to study sustainability effects in this research. These are namely: economical, environmental and social pillars. Global Reporting Initiative (GRI) identified a number of indicators for studying sustainability. These are namely: economical, environmental, labor practices and decent work, human rights, society and product responsibility. After studying our industries, we have identified a number of indicators that are suitable with GRI principles to study sustainability impact of the selected industries. Reasons why this research does not cover all of the indicators provided by GRI are “the current level of integration of AM into our selected industries” and “availability of the data for conducting this study”. For the economical pillar, we have looked upon indicators such as cost-effectiveness, material input costs and decentralized production. These are linked to GRI’s economic performance and indirect economic impacts. For the environmental pillar, we have chosen to take waste reduction, energy efficiency and material efficiency into account. Eventually, this led us to also consider carbon dioxide emissions and energy consumption data provided by Gebler et. al (2014). These indicators are connected to GRI’s materials, energy, emissions-waste and transport indicators. For the social pillar, we have studied transformative changes that AM is expected to bring to the society. These are namely: consumer integration into production, home manufacturing, decentralized production and automation—which connects to the loss of jobs—. These are connected to GRI’s local communities, inclusivity and employment indicators. For addressing current sustainability implications of AM, we have highlighted the developments we have acquired from our sources, therefore drawing a qualitatively driven conclusion for the benefits and threats regarding AM and sustainability.

3.1 Collection of Data

Collection method for empirical data in this research derives from our view of the current literature, various industry reports, company websites (Stratasys; Airbus; Boeing; General Electric; EOS; 3D Systems; Concept Laser; ARCAM), respected websites that provide useful information on the development of AM (3ders.com; 3dprinting.com; 3dhubs.com; 3dprintingindustry.com; futurism.com) and research institutions. Reasons behind the selection of these sources are the given limitations of this research in terms of allocated time and allocated resources. Therefore, only publicly available sources have been used and cited. Given the sensitivity of AM R&D, many companies and research institutions have refused to share detailed specifications and data regarding AM machines, and products that were made with AM

technologies. Therefore, we must state that our findings are relatively limited to what previous research provided and what public data suggests. However, this research also managed to add useful contributions for the future research in AM and sustainability field.

The primary data for assessing the sustainability of aerospace and medical sectors for the close future is taken from Gebler et al. (2014). Due to comprehensiveness and quality of the data in terms of cost savings, energy efficiency and carbon dioxide emissions, Gebler et al. (2014) is the ideal choice for our research. Additionally, this research does not have the means to acquire further data from other sources such as industry reports due to the budget limitations, thus, data from Gebler et al. (2014) is the only suitable candidate for such data acquisition. Our choice from the scenarios of Gebler et al. (2014) will be high market potential, high changes in cost intensity, high change in energy intensity and high change in carbon dioxide emissions intensity. This leads to the results Gebler et al. (2014) for their 4th scenario which means maximum benefits in terms of all the given indicators. Finalization of our results will be adjusted accordingly to these indicators. Our findings in terms of the developments in the aerospace and medical industries suggested that AM technology adoption will see a constant rise. Additionally, with the developments in terms of capabilities of AM, our results indicated that will be seeing more cost-effectiveness and more energy efficiency during the manufacturing of additively manufactured products. Due to the potential of AM to shape industries in terms of economical and environmental benefits with additional social changes it is expected to bring, our choice for the usage of the data is also supported.

3.2 Disruptive Innovation Framework:

For studying disruptiveness of the AM, we have chosen to study business models, market developments and capabilities of AM that were not available with conventional manufacturing methods. In order to put our findings into an order, we have prepared a framework to apply for disruptive innovation theory. Hang et al. (2011) proposed a new framework to study disruptive innovation theory. Their framework was built upon previous discussions by various scholars (Christensen, 1997; Yu and Hang, 2010; Christensen, 2006; Paap and Katz, 2004; Rafii and Kampas, 2002; Keller and Husig, 2009; Christensen et al., 2004; as cited in Hang et al., 2011). By looking at the strengths and weaknesses of the disruptive innovation studies, Hang et al. (2011) suggested a new approach using drivers of market positioning, technology and other favorable drivers. Results of the drivers were

indicated as “yes” or “no” to simply findings. Drivers provided by Hang et al. (2011) and selected for our market positioning study are:

1. Viable business in the low-end market
2. Viable business in a new, niche market
3. Are incumbents in the main-stream market willing to run away or ignore the initial disruptors?

For that, we also added one driver we thought that would be appropriate for market positioning:

4. Is the market share of the disruptor at a constant growth?

For technology driver, we have selected following drivers from Hang et al. (2011):

5. Adequate for a foothold in the low-end market
6. Adequate for a foothold in a new, niche market
7. Could be further improved in performance and price/performance
8. R&D needed to improve the disruptive technology is feasible, affordable and well executed

Hang et al. (2011) stated that depending on the studied technology/development, it is possible to add further favorable drivers. For AM, we will be looking at the following drivers:

9. Favorable life-style changes
10. Environment-friendly properties
11. Ability to produce products that were unavailable with previous technologies

Summarizing our framework in a figure, we have identified three main sections with a total 11 drivers. If “yes” overtakes “no” with a ratio of 4:1, our case will then be identified as a disruptive innovation. The reason why we have chosen this ratio is to make sure that most of the drivers are in favor of the disruptiveness of AM, therefore reducing the error margin of our findings. “Yes” and “no” options will be scored from 1-5 in order to reach to a more detailed conclusion. The framework was applied fully for the aerospace industry. For the medical industry, we have disregarded the driver of “is the market share of the disruptor at a constant growth” since we don’t have data to study such impacts. In appendix 1, we indicated the details the drivers and how we would look at each.

Below, Figure 3.1 presents our framework.

Drivers	YES	NO
MARKET POSITIONING		
Viable business in the low-end market		
Viable business in a new, niche market		
Are incumbents in the main-stream market willing to run away or ignore the initial disruptors?		
Is the market share of the disruptor at a constant growth?		
TECHNOLOGY		
Adequate for a foothold in the low-end market		
Adequate for a foothold in a new, niche market		
Could be further improved in performance and price/performance		
R&D needed to improve the disruptive technology is feasible, affordable and well executed		
OTHER FAVORABLE DRIVERS		
Favorable life-style changes		
Environment-friendly properties		
Ability to produce products that were unavailable with previous technologies		

Figure 3.1: Disruptive Innovation Framework

4. ANALYSIS

In this section, we have looked at the developments regarding AM and 3DP in the aerospace and medical sectors. By looking at specific cases, we have managed to identify current usages of AM in these sectors. Main factors we have looked for the aerospace industry were *resource efficiency, energy efficiency, production times and overall product quality improvements*. For the medical sector, we have studied factors such as *production times and overall product quality*. Reasons we have not incorporated our factors of *resource efficiency and energy efficiency* for the medical sector was the lack of resources in terms of qualitative and quantitative data. Considering the fact that the medical sector has different priorities than the aerospace industry, our current distribution of factors is suitable to contribute our overall goal of researching sustainability of AM technologies while also contributing our goal to understand whether AM is a disruptive or a sustainable innovation. In this section, indicators and contributions of AM in the sectors are highlighted with bold characters in order to give a better understanding of the discussion.

For studying the effects of AM to businesses, we have specified how businesses are developing business models with AM adoption and how current business models might be changing with such adoption. We also studied supply chains to see how AM adoption is also effecting logistics sector as a spill over. By looking at decentralization of production, we also have managed to come up with results regarding economical, environmental and social benefits of AM adoption.

4.1 AM in Aerospace Industry

Aerospace industry was an early adapter of new technologies throughout its history due to its constant innovation trends and huge R&D properties. Examples of such early adoptions are digital design features such as CAD/CAM and usage of carbon fiber in aerospace products. Another driver for aerospace to take such steps is the need for higher quality aircraft and spacecraft in terms of material efficiency, cost reductions, structural integrity, durability, need for lightweight designs and consumer demands for more capable and advanced technologies. Joe Hiemenz from Stratasys (one of the major suppliers of 3DP technologies) stated that the aerospace industry is at the forefront of adopting new technologies and therefore, leading other industries to adopt such technologies in light of achievements made in the aerospace industry. Therefore, Hiemenz (n.d.) mentioned the aerospace industry as a “trendsetter” for AM technologies for other industries to follow. To comprehend AM developments in the aerospace industry, we looked at specific developments in the industry with AM adoption. In each case, we have looked at factors such as *material usage, waste*

reduction, production speed and cost reduction when they were available. We have also studied the information from reports and developments obtained from respective resources such as companies, industry-specific websites, industry-specific journals and academia.

Market Developments

Haflich (2017) mentioned recent developments of AM in aerospace industry citing Wohlers Associates' annual report of 2016 on AM. He mentioned that raw material market in the United States for AM in the aerospace industry reached to US\$ 769 millions in 2015. Haflich (2017) added that AM machines sold to aerospace industry in the United States alone have reached to 808 machines as of 2015 compared to the 105 machines sold and delivered back in 2010. Orcutt (2016) also referring to Wohlers Associates stated the rise of AM machines sold to the aerospace companies. A more detailed insight indicates that there were 550 machines sold in 2014 and 353 in 2013. Comparing these numbers with a record breaking 808 machines in 2015 shows increasing adoption of AM in the aerospace industry. Orcutt (2016) sees this as metal 3D printing becoming a mass manufacturing technology. Clearly, there is an increasing demand for AM in aerospace industry with a tremendous growth rate for such demand. General Electric alone needs 1000 AM machines over the decade since the company is one of the forerunners to adopt AM and 3DP with their latest LEAP engine. Haflich (2017) also stated that there is an increasing demand in the United States for material powders for AM processes and expected growth in powder markets are 25% annually by 2020. Metal Powder Report (2014) added that as for 2014, 3DS alone supplied 100 printers for aerospace manufacturers. 3DS also added in the report that aerospace engineers prefer 3D printers due to fuel savings and fast production. Metal Powder Report (2015), also mentioned that the US defense industry is also interested in the 3D Printer applications. The report also stated that major companies such as Lockheed Martin, Northrop Grumman and Honeywell are working with 3D Systems (3DS) company to provide advanced manufacturing applications for the aerospace and defense products using 3DS technology. In light of these market developments and aerospace sector's role as an early adapter of AM technologies, it is safe to assume that the demand for AM in the aerospace technology will continue to rise. Therefore, creating more opportunities for AM systems developers to enhance their sales and increase the market volume of 3D printers and other AM machines.

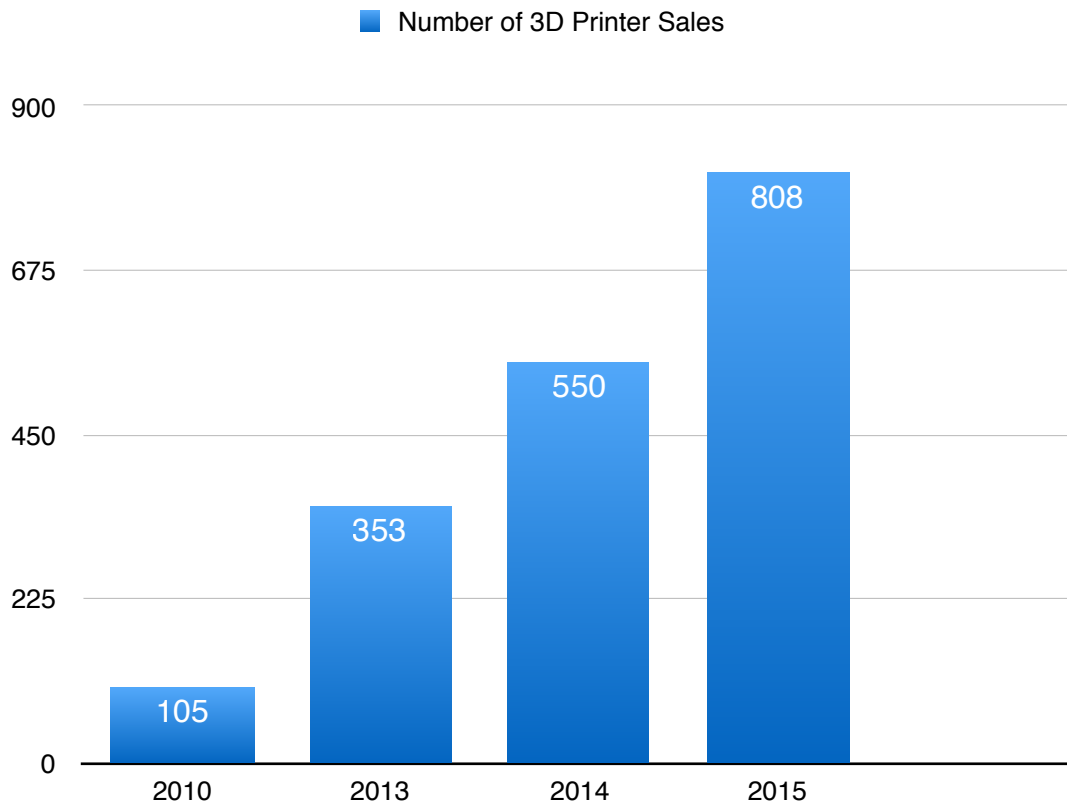


Table 4.1: 3D Printer sales to the aerospace industry in the US between 2010-2015

Case-Specific Developments Concerning Material and Waste Efficiencies, Production Speed and Lightweight Components

From various industry reports, we have seen that the additive manufacturing and 3D printing methods have led to better products for the aerospace industry. Dr. Rob Sharman from GKN Aerospace stated that AM enables optimization of the whole production system. Dr. Sharman also added that “AM is not about what you can make today, it is about what you can’t”; eventually, referring to the design freedom and complex geometry of products made with AM (Nickels, 2015). Fraizer (2014) stated that the US Navy views AM as an important method to develop future naval aircraft since AM usage is expected to result in *enhanced operational readiness*, **reduced energy/fuel consumption** and *reduced total costs of ownership*. Traditional airplane parts that were remade using LaserCUSING method are resulting in 30% more **lighter** final products than the traditional ones and they offer more durability by replacing aluminum with titanium as the component (Nickels, 2015). Nickels (2015) stated that this new method creates only 5% **waste** compared to the previous manufacturing methods followed by 75% **reduction in the raw materials usage** since the only amount of raw materials that were needed are being used for manufacturing. Prof. Dr. Emmelmann added that with conventional milling processes, up to 95% of waste was produced in some cases. But with laser melting (an AM

method), only 5% waste is produced and this waste is **recyclable**. Referring to buy-to-fly ratios, this was seen as a huge benefit since *material efficiency* is at its maximum compared to conventional methods (Nickels, 2015). As an addition to these numbers, The Economist (2011) stated that 90% of the aircraft-grade aluminum is cut out during the production, thus resulting in a huge *waste generation* with conventional production methods. The Economist (2011) added that 3D printers are using **less energy** than conventional production methods. In some cases, printed products are 60% lighter compared to the previous products. This is again huge contribution for aerospace industry since lightweight products will result in a better life cycle in terms of fuel efficiency. Also, aircraft-grade aluminum and other metals are expensive. Thus, reducing material usage up to 90% also provides considerable cost reductions, while promoting environmental gains such as waste reduction and raw material efficiency. The Economist (2011) also stated that over 1000 aluminum parts in a typical aircraft are printable. This again pointed out that there are a lot of opportunities for AM in the aerospace industry. Considering the fact that 1 kg reduction in an airplane results in US\$ 3000 **fuel savings** throughout a year is desirable for both manufacturers and aircraft operators. Even though we have reached to different numbers from various sources, it is clear that AM is offering better products than the ones manufactured with conventional methods. Moving on, we have looked at specific cases regarding these developments in the aerospace industry.

EOS is one of the first companies to offer AM for industry users that was formed back in 1989. In their website, there are useful insights in terms of AM usage in aerospace industry. EOS mentioned a recent breakthrough in the aerospace industry with the help of AM technology. For the outer space, costs of placing satellites into the orbit are extremely high. Estimated cost for 1 kg of material to reach the outer space exceeds €20.000. While a rocket launch into orbit is a multi-million US\$ operation, cost-reductions are extremely beneficial for launching companies. Given this high cost, there is a need for design optimization for satellites. With the *flexibility, material and design optimization* of AM, EOS managed to create a new satellite antenna bracket. Reducing the **weight** of final component from 1.6 kg to 940 grams shows a significant reduction, therefore causing reduced launch costs. EOS also stated that due to the extreme environment of space launches, a reduced design also needed to be supported by a strong component. With the higher durability of AM products, this problem was also solved. This development is significant for aerospace industry since it proves that with AM, design optimizations can result in *lighter and stronger* products to be put in the orbit, thus reducing the price tag of placing a satellite in the orbit.

EOS stated that all of the required tests were successfully passed and their new antenna bracket received certification to be used for outer space operations. In light of this development, it is highly expected that more satellite components would undergo a redesigning process for being additively manufactured. Overall **cost reductions** would mean an important contribution for economical sustainability while reducing fuel needs for rockets and also contributing to the environmental dimension of sustainability. According to EOS, Airbus Defence and Space also started to use AM for satellite components. Connective brackets in satellites need to withstand temperatures ranging from -180 to 150 Celsius, therefore design and materials needed optimization. Conventionally produced carbon components did not meet Airbus' requirements for such conditions, therefore a new design phase was initiated. 3D printing new components resulted in significant improvements. According to Airbus engineers, *weight reduction* of 300 grams per component was reached, resulting in 900 grams total since 3 connective components were needed. Additionally, 20% *cost savings* during the whole production was achieved and production was shortened to less than 1 months with 15 days of reduction compared to the previous method. Not just the payload for outer space operations, but also rockets and boosters were also improved with AM technologies. SpaceX has been using AM for their rockets and spacecraft propulsion systems since 2014. By 3D printing Main Oxidizer Valve for their Merlin 1D engines used in Falcon 9 rockets, SpaceX proved that additively manufactured products are suitable for space operations. Taking their AM usage one step further, SpaceX produced a SuperDraco engine chamber entirely by printing it. Initial tests suggested that 3D-printed part is capable of withstanding immense amounts of temperatures and pressures of the complex features of the engine's functions. SuperDraco engine chamber is now fully operational and is capable of being used in real operations. Haflich (2017) mentioned a recent development by Lockheed Martin to incorporate AM into satellite manufacturing. With electron beam additive manufacturing (EBAM), Lockheed Martin is also building propellant systems for satellites using titanium to create propellant tanks. We have seen AM is an ideal choice for space operations due to additively manufactured product's suitability for space missions with a higher quality of technical properties compared to conventionally manufactured products.

Brooks (2014) mentioned a collaborative study by Airbus and EOS in order to **reduce weights** of aircraft components. The study aimed to conduct a life cycle analysis of additively manufactured aircraft components and investigate energy efficiency and weight reduction. Airbus produced A320 nacelle hinge brackets using

EOS' DMLS system. With AM, new brackets were manufactured using titanium compared to the conventionally manufactured steel brackets. Life cycle study suggested that with AM, there are considerable savings in terms of **weight reductions and carbon dioxide emissions**. Carbon dioxide emissions of the brackets over the whole life cycle were reduced to 40% and plane's weight was reduced by 10 kg. In terms of buy-to-fly ratios, this is a considerable reduction for an aircraft component while a significant contribution to environmental sustainability by carbon dioxide emission reductions. Orcutt (2016) stated that companies such as General Electric (GE) and Pratt & Whitney are using AM technologies to produce engine parts. Orcutt (2016) referred to GE for manufacturing fuel nozzles, apparatus for housing temperature sensors and parts of turboprop engines. Especially with the new fuel nozzle, there is a 25% weight reduction per part compared to previously manufactured conventional fuel nozzles. According to GE, LEAP engine delivers 15% fuel consumption improvement when compared to previous CFM56 engines. Orcutt (2016) also indicated that GE already has 10.000 orders for the new fuel nozzle and is planning to manufacture 30.000 fuel nozzles annually. GE also added that they are currently world's largest user of additive technologies in metals and the company aims to produce 100.000 3D-printed parts by 2020.

For the **energy consumption** of AM, Nickels (2015) stated that compared to conventional methods, AM has a very little energy efficiency advantage overall in the production phase. However, our findings suggested that with the same amounts of energy being used in the production, there is a raw material reduction of up to 75% and energy efficiency of AM machines are increasing. Consideration of energy efficiency in the aerospace industry not only focuses on the production phase, but also the overall life cycle of the product that results in fuel efficiency. EOS stated that with AM technology, aircraft components are lighter and much tougher. EOS indicates that with AM, there is a weight reduction of 40-60% compared to conventionally produced components. Lightweight components mean less fuel consumption and less carbon dioxide emissions, thus a significant contribution to environmental dimension of sustainability. Germany-based Concept Laser company produces bracket connectors for the new Airbus A350 XWB using AM. Previous bracket connectors were made with aluminum using traditional milling methods but with AM, same components were made with titanium instead. While resulting in a stronger product, there was a weight reduction of 30% compared to the previous models. Therefore, effecting the fuel consumption of the plane by lighter parts, but also increasing the load capacity of the aircraft was achieved. This not only contributes to the sustainability, but also enables

companies to benefit from reduced weights by increased carrying capacity, thus resulting in more profitable flight solutions (Nickels, 2015).

According to Concept Laser, one important contribution of AM in the aerospace industry is the reduced dependence on tools. Since no tooling is required in AM, this can ***reduce the costs and shorten the whole process*** by up to 75% (Nickels, 2015). An example given here is that with AM, a component is made in a month compared to 6 months with conventional manufacturing methods. An advantage of AM is not just to produce components faster and cheaper, but also producing lightweight and more durable products. As we discussed before, about the usage of EBAM by Lockheed Martin, EBAM allowed Lockheed Martin to cut production from 18 months to 6 months. Airbus stated that have been using their mini aircraft project called Testing High-tech Objectives in Reality (THOR) as a testbed for futuristic aircraft technologies. 90% of the first THOR was made with 3D printed parts using plastic polyamide powder. According to Airbus, it took a total 8 weeks and 3 days to manufacture and fly THOR. Airbus stated that there are further versions of THOR under development that are allowing modular aircraft designs offering greater flexibility in airframe and structural testing. What makes THOR significant is that it is the first aircraft made almost entirely out of 3D printers and successfully flown. Further expectations from new THOR models are to deliver metallic aluminum wing, biomimicry-based designs and artificial intelligence integration allowing THOR to land on its own by identifying obstacles on the runway and determining whether it is safe to touchdown without support from any ground infrastructure (Airbus, 2016).

Potential of Change Brought by AM to the Overall Structure of Aerospace Industry

Nickels (2015) made an interview with Prof. Dr. Emmelmann, the CEO of Lazer Zentrum Nord GmbH, discussing the effects of AM on the aerospace industry. An important insight given by Prof. Dr. Emmelmann in the interview was the reduced needs for a centralized production scheme. With the ability to produce required parts on-demand and on-sight, logistical needs to transport parts from one location to another would decrease. While saving a lot of time during the maintenance of the aircraft, this would have implications for faster and cheaper maintenance, thanks to AM technology. Another contribution of this flexibility is towards the financial benefits deriving from decreasing needs to maintain large warehouses with huge inventories. With the production occurring on-demand and on-site, ready-made parts will not be

needed anymore. Thus, resulting in a lesser inventory waste and fewer maintenance costs for such warehouses and inventories.

In terms of material efficiency and material properties, AM offers better products to be specifically considered in aircraft engines. Due to high temperature resistant and flame retardant polymers, metal products are of higher quality and more solid. This leads to more suitable products for engines since higher temperatures would mean better operational capabilities of engines, thus making components made with AM an ideal candidate for engine parts. (Nickels, 2015). This may overall change the behavior in the aerospace industry to use new materials with AM while retiring conventional materials and methods for engine production and other aircraft components respectively.

Conclusion

Looking at the given developments in the aerospace industry, have observed that with increased AM utilization, better products have emerged in terms of **material usage, waste reduction, production speed and overall product quality**. It is safe to assume that increasing AM adoption by the industry is leading to lighter products that are eventually contributing to environmental dimension of sustainability due to reduced carbon dioxide emissions and less fuel consumption. With overall improvements on the components life cycles, economical benefits are expected to be huge, only if more and more components are to be produced with AM technologies. Energy efficiency during the production is still an issue to be addressed since initial studies suggest there aren't significant differences between conventional methods and AM. However, considering the fact that AM is in a momentum of constant development, we can expect more energy efficient AM and 3DP machines to change this gap. More importantly, AM currently compensates its **lower energy efficiency** gap with waste reduction and material efficiency. With less waste being produced and less raw material input is required, AM gains a significant economical benefit for aerospace industry considering high buy-to-fly ratios. Dr. Rob Sharman from GKN Aerospace stated that AM enables optimization of the whole production system. Dr. Sharman also added that "AM is not about what you can make today, it is about what you can't"; therefore, referring to the design freedom and complex geometry of products made with AM (Nickels, 2015). However, Dr. Sharman also added that one of the biggest challenges ahead of AM in aerospace is the generation of data and quality assurances, since the technology has not reached its maturity and is in a process of constant evolution (Nickels, 2015). This therefore, suggests that more research is

needed to provide quantitative results and case-specific studies to contribute our overall understanding of AM technologies' effects in the industry.

Considering the *design freedom, new geometries, cost-efficiency, material efficiency, waste reduction and higher production speeds* brought by AM to the aerospace industry and the possibility to create new components and products that were not available to the industry previously; we conclude that AM adoption has already started to cause significant effects and changes in the aerospace industry of today, and is expected to bring more changes in the following years.

4.2 AM in Medial and Biomedical Industry

Increasing usage of 3D printer usage in the medical industry has led to many applications. Bioengineered tissue, bone, teeth and even organs are becoming a reality. Still, there are a lot of developments needed. Gross et al. (2014) mentioned the limitation to individualized treatments due to the infeasibility of autogenous tissue sampling as a concern. Their article also added that with the ability to customize a 3D-printed scaffold would enable creating required products without requiring patients own tissue for scaffold formation. With further possible enhancements of the current technology, medical sector could produce efficient and patient-specific solutions that would lead to better and faster treatments/replacements. With the enlightenment of these developments mentioned by Gross et al. (2014), we should look more into the application of 3D Printers in medical and biomedical sectors. Before moving on with the current usage of 3DP for medical purposes, US Food and Drug Administration (FDA) underlines some of the current procedures. FDA (n.d) specifies current medical products made by 3D Printers as instrumentation, implants and external prosthetics. According to FDA, printing alive tissues and organs are at early stages of development. FDA also highlighted powder based fusion technique as a common 3DP approach used in the medical sector. Powder based fusion uses fine powder of materials (metal or plastic) and creates layers upon layers by melting material to the previous layer and powders nearby it by using an electron or a laser beam. FDA also stated that they are currently using powder based fusion to test the technique in order to understand the capabilities of the technique and explore public health benefits. Since powder based fusion is a standard procedure that doesn't have patient-specific features, FDA also mentioned there are patient-specific printers also available to manufacture medical products. Moving on, we have looked into more case-specific developments that led to promising early results for 3DP in the biomedical sector.

Zhu et al. (2016) underlined the increasing usage of 3D printers in terms of tissue engineering and regenerative medicine. They also added that recent developments in 3DP technology led biomedical engineers to use 3D printers as a transformative tool for their applications. By looking at specific developments, we are assuming that the usage of 3D printers is reaching a wider field of application day by day in line with the developments in the technology. The possibility of creating alive tissues, implants and organs would pave way for even wider ranges of applications of 3D printers in the sector. With the possibility of creating alive tissues through bioprinting, the *need for animal test subjects* for drug testing and cosmetics testing has already been reduced. With alive tissues, we could obtain better information on specific product's effect on humans while saving the lives of many lab animals. It is also possible to say that with this capability, *responses to epidemics* could be faster and more efficient than current methods. With decreasing costs of 3D printers, worldwide proliferation of the technology is achievable within short to medium term. This may as well increase *local responsiveness* for biomedical product needs while saving costs of transferring samples, shipping products and reducing the waiting time for patients and researchers. Possibilities emerging from the ability to print alive tissue also paves the way for personalized organ printing.

Bioprinting Applications of AM

Yoo (2015) mentioned that 3D bioprinting creates the flexibility to produce on-demand personalized organ printing through building functional biological constructs by dispensing groups or individual units of cells into bio-scaffold materials and extracellular matrices. Yoo (2015) also added that our current knowledge of composing functional cells along with the appropriate epicellular environment is at an infant level. Therefore, current methods need to be improved and our understanding of using 3D bioprinting needs to be enhanced. By looking into some of the current achievements by the sector using 3D printers, we have reached to a better understanding towards the development and usage of the technology.

Krassenstein (2015) has taken a Russian company's bioprinting developments into account. Russian-Based company 3D Bioprinting Solutions is challenging 3D-printed organs with its 3D-printed thyroid gland to treat a mouse effected by thyroid cancer. Krassenstein (2015) stated that the company has chosen thyroid specifically for its simplicity and the fact that it is 16th most common cancer affecting 300.000 patients every year. The process is very similar to other **3D-printed organ** trials.

Stem cells extracted from fat cells are injected into a scaffold with hydrogel. After hydrogen dissolves, the organ is functional. 3D Bioprinting Solutions mentioned that rejection of the thyroid gland by the subject is highly unlikely, since the product is made from subject's own stem cells. According to Krassenstein (2015), the company also stated that they will be able to 3D print other organs, and aiming to print a kidney by 2018. In a follow-up article by Scott (2015), company's announcement of success was mentioned. On November 2015, 3D Bioprinting Solutions has successfully implanted a 3D printed thyroid gland to the mouse.

Lozano et al. (2015) conducted a novel study to test the achievability of 3D printed brain tissues. They developed a new method to bioprint 3D brain-like structures consisting of discrete layers of primary neural cells encapsulated in hydrogels. They also justified their study as giving the possibility to create 3D *in vitro* representation of brains would furthermore give the possibility to study traumatic brain injuries, physiological learning and memory. Lozano et al. (2015) stated that hydrogels were already being used for many decades in the biomedical sector. Lozano et al. (2015) used a ***new material*** called gellan gum in their research. Selection of gellan gum was justified in the article as gellan gum had unique and better properties including gelling temperature, texture, gel strength, clarity, the rate of gelation and ability to dissolve in water. Therefore, gellan gum was chosen over hydrogel in this study. Additionally, Lozano et al. (2015) said that they have developed a new method of bioprinting called "handheld reactive bathless printing process". Their aim was to successfully create multi-layered, brain-like tissue. Eventually, they have succeeded and opened a new way for 3D bioprinting by successfully printing brain tissues. Successful indicators on encapsulation, survival and networking of primary cortical neurons and glial cells were shown. With this new method, applications ranging from *behavior studies, understanding brain injuries and neurodegenerative diseases to drug testing* can now be conducted (Lozano et al., 2015). Another development for the brain-tissue generation that links closely to brain tumors was achieved in 2016. In a news article by Russell (2016), a new development by Scottish scientist to create 3D printed brain tissues was highlighted. Researchers at Heriot-Watt University managed to 3D-print brain tissues with several types of brain tumor in a laboratory. Researchers stated that with this new development, the need for animal testing on brain tumor drugs has been eliminated. Moreover, researchers stated that tumors grown in laboratory taken from patients brains behave differently than a tumor inside human brain since the environment is relatively different (Russell, 2016). With this new method, 3D printed brain tumors are mimicking the real behavior of tumors inside the

human brain, thus giving the possibility to study their nature more efficiently and testing medication techniques more precisely (Caparas, 2016).

Allen et al. (2015) conducted an experiment using hydro gel infused with human cells called A431 human epithelial carcinoma. Before human cell infusion, researchers conducted several experiments at different levels to prove the success of their method, which was coating plastic micro-particles with 40 base pairs of DNA. Afterwards, forming gel-like materials that could be used in a 3D printer. The experiment resulted in success with human cells and generated a new method for 3D bioprinting. Allen et al. (2015) also stated that with more advanced DNA computation, they have the possibility to reach to better results by algorithmically determining the assembly processes at nano and micro scales.

Another fascinating development includes 3D printers usage for medical purposes is the recently developed **artificial ovaries**. Fan (2016) mentioned this new development in her article by pointing out a study that used 3D printers to create scaffolds that were infused with immortalized human cells. Initial studies suggested that this could be a feasible solution for infertility in women caused by problems with ovaries. A test was conducted on mice. Ovary of the mice was first surgically removed and then 3D-printed implant was introduced. Results have indicated that hormonal functioning of the mice quickly recovered and blood vessels also formed in and around of the implanted ovary, thus providing nutrition and washing away the waste. Later on, mice gave birth to healthy pups (Fan, 2016). This method is promising for human trials since many women suffer from conditions related to ovaries, thus being unable to give birth. 3D printed ovaries could be the solution for infertile women to have children.

American Chemical Society (ACS) (2016) highlighted in a public release that elderly, athletes and others suffering from injuries and arthritis can lose their cartilages. But recently, a new research indicates that a new method was found for **3D bioprinting cartilage** tissue by an ink containing human cells. ACS (2016) also stated that this development was successfully tested in an *in vivo* mouse model. Also in the public release, ACS quoted Paul Gatenholm for explaining their works. Gatenholm stated that their team was working especially with ear and nose in order to create/repair cartilage damaged due to injuries or cancer. Gatenholm added that their new method is successful *in vivo* testing with mice after 60 days of extensive trials. It is also important to state that further tests are needed in order to start human trials.

Next goal of this research group is to create a **3D-printed skin** by working with a cosmetic company (ACS, 2016). Wake Forest School of Medicine's Institute for Regenerative Medicine (n.d.) stated that they were able to 3D-print skin to treat skin burns. Institute for Regenerative Medicine (n.d.) explained the process. Firstly, an "ink" is created consisting different types of skin cells that would be defined accordingly to the degree and depth of burn, which is detected using laser scanning. After the laser scan is complete, cells are arranged and mixed accordingly by arranging a patch that is 1:10 size of the wound. This 1:10 size patch is enough to grow skin cells necessary to apply to the burn. What we discussed here is mentioned as phase I by the Institute. Institute of Regenerative Medicine (n.d) stated that in the second phase of their research, they will try to observe whether stem cells found in amniotic fluid and placenta could be used to generate skin cells for printing. Phase II is expected to conclude 5 years after Phase I, which was conducted in 2015. Another development for skin printing is made by using stem cells and hydrogels. Javelosa (2016) mentioned that with the new "biopen", surgical scaffolds were created and hardened using ultraviolet light, thus creating permanent tissues with this handheld printer. This new "biopen" is still under development but sheds a light that skin printing could soon be the reality with very small and efficient devices, made possible by 3DP technology.

Bone Printing and Dental Applications of AM

Apart from organs and tissues, there are also developments to improve implants such as bones and teeth. Creighton (2015) reported in her article at Futurism that scientists successfully implanted a **3D-printed skull** to a patient through surgery. In the article, she has also quoted lead neurologist Ben Verweij stating "Using 3DP, we can make one [skull] to the exact size. This not only has great cosmetic advantages, but patients' brain function often recovers better than using the old method". Galeon (2016) mentioned a new material that could potentially revolutionize **bone printing** in medical sector in his article in Futurism. He added that researchers in Northwestern University managed to mimic human bone with an ink made from a natural bone mineral called hydroxyapatite. Researchers mixed this mineral-based ink with PLGA (mineral-binding polymer) that made implants elastic. Once these "would-be bones" placed in patient's body, blood vessels observed to rapidly infiltrate them, therefore reacting to hydroxyapatite and turning implants into real bones. Researches also stated that they were surprised to see such reaction by patient's body to treat to the implant as if it was a natural incomplete bone. Iain Hutchison —one of the researches— mentioned that patient's body was reacting to this implanted "would-be

bone" matrix, and gradually turning it into a real bone without having to implant stem cells or other growth factors (Galeon, 2016). This further proves the possibilities 3DP offers in medical sectors with ***cheaper and more effective solutions*** compared to conventional medical methods.

A new state of the art 3D printer was built by a team from the University of Toronto for 3D-printing bone implants. With this new 3D printer, ***new materials*** were used to print better bone implants by incorporating calcium polyphosphate into implants. This printer uses ultraviolet light to bind materials together while creating canals for nutrition to circulate to allow the bone to grow (Gallego, 2016). Scientists also made a breakthrough using 3D printed titanium ribs for a Spanish patient suffering from chest wall sarcoma, which is a type of cancerous tumor growing around the rib cage. According to Knight (2015), 54-year-old Spanish patient received a state of the art titanium rib cage made with 3DP. The 3DP process was highly sophisticated since it used titanium as the material and needed a customized interface to complete its task. 1.3m\$ Arcam printer was used in the process, building implant layer by layer with its electron beam. After the rib was complete, the patient was taken into surgery and titanium rib cage was successfully planted. Results were delivered by Australian Industry and Science Minister Ian Macfarlane on September 11, 2015. The success of this project with the help of Melbourne-based medical device company Anatomics and Arcam printer is another breakthrough of 3D printing solutions for biomedical applications (Knight, 2015).

Yu et al. (2015) mentioned a development that could be called a breakthrough for 3DP in biomedical applications. A research team in the University of Groningen led by Andreas Herrmann successfully developed a ***3D-printed coated teeth*** by applying a new antimicrobial material into existing dental resin polymers. As a result, they have achieved antibacterial teeth made by 3D printers. This is called a breakthrough since this would prevent bacterial damage towards dental implants, therefore helping to fight against tooth decay. Initial studies by the group have shown that 99% of the bacteria were successfully eliminated with this ***new material mixture*** (Yu et al., 2015). There is also good news for the prosthetics with emerging 3D printer usage in the sector. Corpuz (2016) highlighted a new initiative to ***customize 3D-printed arms*** by enabling ***patients to download and print their own bionic arms***. Open Bionics firm specializes in delivering 3D printed prosthetics with much ***cheaper and faster solutions***. In fact, the company can build a fully customized and a fully functioning arm in just three days, while retaining the costs 20 times cheaper than

traditional methods of prosthetics manufacturing with the help of 3D printers (Corpuz, 2016). This paves way for **affordable** and **customized** prosthetics that are constructed **locally** by 3D printers.

Pharmaceutical Industry and AM

Pharmaceutical developments have also created significant examples of 3D printer usage for medical purposes. In Science News Journal's (SNJ) article (2016) on **3D-printed drugs**, we again connect to the dysphagia, but this time from a different perspective. Aprelia Pharmaceuticals became the first company to develop, test and acquire an FDA approval of a prescription drug manufactured by 3D printers. This new drug dissolves significantly **faster** than other medicines with same properties and purposes, which also paves the way for a more **personalized dosage/treatment** opportunities for pharmaceutical companies and patients. One other contribution of this new drug is that due to its extremely fast dissolving feature, the drug is highly suitable for epilepsy patients. With this rapid dissolving of the drug, epilepsy patients managed to swallow the drug faster, and also elders with dysphagia had received the drug more easily (SNJ, 2016). Aprelia Pharmaceuticals might be the first company to get FDA approval to sell their 3D-printed drug in the market but still, there are many pharmaceutical companies conducting R&D, laboratory testing and FDA approval procedures at the moment. We will definitely see more 3D-printed medication hitting pharmacy shelves in the upcoming years with more innovative and flexible treatment possibilities. In order to achieve more 3DP integration into pharmaceutical applications, researchers from National University of Singapore (NUS) announced that they are currently developing **3D-printed pills** (NUS, 2016). In a press release, NUS engineering team stated that they are developing a novel technology to print customized tablets for **personalized medicine**. By using 3D printers, engineers stated that they have developed 5-prong shape pills that release the required medication into the patient with "5 pulses in different times", thus eliminating the need to take multiple pills throughout the day. Asst. Prof. Soh from the team mentioned that this new technique is more **cost-effective** than current mass-production methods and gives doctors flexibility to customize medication and dosage specifically for patients' needs. Also, computer software gives doctors ability to arrange the tablets to pulse at specified times of the day. Another possibility comes here is the combination of different medicines into a single tablet, thus **saving costs** of producing different medicines, therefore, calibrating complementary effects of different drugs (NUS, 2016). Another flexibility this method created was the utilization of commercially available 3D printers, thus eliminating process-specific 3D printer

creation and saving costs related to such developments. This could also give the possibility to clinics and hospitals to locally produce tablets ***on-demand*** and on the spot.

Other Medical Applications of AM

One 3DP application that connects medical sector and food sector is the EU's "Personalized Food for the Nutrition of Elderly Consumers" (PERFORMANCE) project. Medina (2015) explained in his article briefly what the project is about. Briefly, PERFORMANCE was a multi-national and a multi-million dollar project that utilized 3DP technology in order to create better ***nutrition solutions for elderly people*** diagnosed with dysphagia. Printable food solutions were prepared in a puree form, of which were also liquid enough to be printed. Therefore this made them ready to eat after printing procedure. The process also adds many flavorings that result in a very tasty meal that is both nutritious and easy to swallow. It was also stated by Medina (2015) that every meal is algorithmically organized for each patient depending on their specific nutritious needs.

More usages are present for 3D printers in the biomedical industry such as ***forensic science*** and ***educational purposes***. Recreation of body models to study internal and external injuries in order to give a better explanation for the cause of wounds are leading better investigations for forensics (Gross et al., 2014). Also, recreation of skulls and bones are giving many new possibilities for forensics. One example given by Gross et al. (2014) was the facial reconstruction of an 18th century individual using the 3D-printed reconstructed skull. This development was not possible before by using conventional methods since the skull was deformed and corroded after hundreds of years of exposure to environmental factors. Another important 3DP contribution in the field of medicine is the education. With the possibility of modeling and printing body parts, skulls and tissues; students are having a better understanding of human body during their practices. Gross et al. (2014) mentioned that with more affordable 3DP, medical schools have more opportunities to use the technology and this increases students' ability to conceptualize biomolecular structures more successfully compared to conventional methods. Another development that also connects to the educational usage of 3D printers in educational usage is not particularly for educational purposes either. Pierce (2017) highlighted the current utilization of 3D printers to give surgeons a chance to practice for complex surgeries before actual surgery takes place. Pierce (2017) described this process by giving the example of a complex surgery conducted on conjoined twins in Florida.

Briefly, twins hearts were physically joined and twins' separation surgery needed to include the separation of their hearts. Since their hearts were very small in size and complexly jointed, a 3D-printed model of the hearts were created using 3D scans of the twins. Then, the surgeon performed simulated surgeries with the 3D-printed model of hearts in order to perfect the procedure, which would then be used in the real surgery. Eventually, twins were successfully separated and are now completely healthy. One dimension this opens is the possibility of ***giving surgeons simulated practices*** before conducting real surgery of complex conditions. Pierce (2017) added that with the help of actual CT, MRI and ultrasound scans; 3D models of organs have been successfully created and printed using 3D printers. One other usage of this particular method is giving medical students a chance to work on realistic models of organs. Pierce (2017) also added that with the usage of hydrogels and artificial blood; these models even bleed when operated on. Pierce (2017) continued that these models even feel like real organs due to materials used in the production of the model organs. These developments are expected to open the possibility to practice on risky and complex surgeries, meanwhile ***giving medical students practical experience***. This process of creating realistic organs with 3D printers is called Simulated Inanimate Models for a Physical Learning Experience (SIMPLE). Pierce (2017) pointed University of Rochester Medical Center as the hub for this creation. Doctors are working with bioengineers in order to create this "faux organs". Proliferation of this process may save many lives globally.

Conclusion

We have seen that in the medical sector, there are a lot of strengths for AM to be adopted. With increasing applications of AM in *tissue printing, organ printing, bone printing, teeth printing, drug printing and educational usages*; AM is earning itself a respected place in medical applications. With the ability to print organs on-demand and on-site, we can expect more lives being saved without the ***necessity of organ donors***. This may shape medical industry and medicine since almost all of the needed organs are obtained from deceased people or healthy individuals. With the ***reduced need for organ transportation***, organ deterioration can be prevented while saving transportation costs of organs from one place to another since this transportation procedure requires sophisticated measures to prevent organ deterioration such as aerial transportation, constant cooling and attendance. Organ transportation procedure is costly and faults in the procedure may result in the loss of the organ that eventually effects the patient's well-being.

With improvements in the bone printing and implant technology, we have observed faster production of implants and bones for those in need with better qualities compared to the conventionally produced products. Even with titanium-based bones and smart prosthetics, we can [one day] achieve better products than our bodies allow. Even though this seems like the concepts of science-fiction, but with improvements in science and technology, enhanced humans are becoming a reality. And 3DP is playing a crucial role for the development of this super-strong and highly capable prosthetics and implants.

Developments in the pharmaceutical industry are leading to better medication for patients. We have seen that with AM, design of a new generation of pills have started. These “smart pills” allow doctors to customize medicine to patients and allows them to manufacture pills on site. Also with the new design features, different drugs can be incorporated into a single pill, thus allowing a reduction of costs for drug manufacturing and better treatment for patients.

Overall, we have seen that AM brings economical benefits to medical sector as well as respective social changes related to medicines and better-looking prosthetics. These social changes might affect behavior of doctors, patients and pharmaceutical companies with new possibilities AM brings. Economical benefits of AM integration into the medical industry are reduced transportation costs of medical products (organs, implants, prosthetics etc.), decentralization of medical product manufacturing, and on-demand and cost-effective production of prosthetics and implants.

4.3 AM and Business Models

There has been an ongoing debate whether AM is forcing companies to create new business models or modify their current models in line with AM adoption. In order to understand such influence by AM, we must look into properties brought by AM to manufacturing processes, distribution processes and production strategies accordingly. In this section, we have discussed new business models deriving from AM adoption. After concluding our findings in terms of business model changes and businesses’ reactions towards AM adoption, we will then look into the new “decentralized production movements” deriving from AM adoption. Finally, we will be looking at the effects of AM adoption towards supply chains and how such adoption might effect established logistics and supply chain behavior of businesses. Our findings in this section will help us to reach a conclusion regarding “whether AM is a disruptive innovation or a sustainable innovation”, but also contribute to the sustainability effects of AM.

4.3.1 Businesses and Their Reactions Towards AM Adoption

Rayna and Striukova (2015) mentioned that with the digitalization of products, we will be seeing tangible objects turning into intangible ones. Therefore, the concept of a product switches from physical objects into a digital representation of such object. By looking at the previous examples in the music industry and movie industry; we have seen that digitized products overtook physical products and disrupted those industries by moving markets and production into a new virtual level. With the proliferation of 3D printers and progressive developments in AM, we are witnessing a shift from physical production into a digital one. This trend was also observed with the introduction of computerized traditional manufacturing methods but with increasing AM practices, digital manufacturing trend has accelerated significantly over past years (Rayna and Striukova, 2015, p. 214). Rayna and Striukova (2015) also stated that it is unlikely to see a total shift of manufacturing from factories to homes due to the economics of scale and feasibility issues in terms of mass-production capabilities of AM. Adopting AM is expected to cause established companies to reconsider their business models, which in turn may change the sustainability impacts of their practices (Despiesse and Ford, 2016, p. 1582). AM is extending product life cycle and changes the centralized focus of production. It is expected that with repair, refurbishment and remanufacturing capabilities of AM, businesses will create product-service business models (Despiesse and Ford, 2016). Rayna and Striukova (2015) mentioned four phases of 3D printing evolution as rapid prototyping, rapid tooling, Direct Digital Manufacturing (DDM) and home fabrication. We have looked into these phases as businesses also developed strategies accordingly. As for the key components of business models, we have also selected Rayna and Striukova's five key components. These are namely: value proposition, value communication, value creation, value capture and value delivery.

Phases	Started	Design	Tooling	Manufacturing	Distribution
Rapid Prototyping	Early 1990s	✓			
Rapid Tooling	Late 1990s	✓	✓		
DDM	Late 2000s	✓	✓	✓	
Home Fabrication	Early 2010s	✓	✓	✓	✓

Figure 4.1: Phases of Additive Manufacturing Evolution (Source: Rayna and Striukova, 2015)

Rapid Prototyping

Aerospace industry was among the first ones to benefit from rapid prototyping capabilities. This has enhanced their capabilities towards better product designs and the ability to foresee how designs would look after the production processes. Similar effects were also present in the medical sector with the ability to prototype new designs of prosthetics and implants. This allowed medical companies to improve overall product quality and design, while having the opportunity to test new materials and technologies that could be useful for the sector. With the emergence of affordable printers and AM machines, SMEs and consumers now have the possibility to benefit from rapid prototyping benefits. Rapid prototyping might have a large effect on creativity, innovation and competition by bringing this capability to masses (Rayna and Striukova, 2015). This is an opportunity for small businesses to utilize this capability by forming business models that could eventually lead to better products. This might effect value creation by SMEs, thus making them available to compete with bigger companies. However, rapid prototyping based business models are limited due to their limitations towards design and prototyping purposes.

Rapid Tooling

Rayna and Striukova (2015) stated that rapid tooling might effect business models in terms of core competences. With its effects on value creation, rapid tooling might change core competences non-core and non-core competences into core competences. Rapid tooling also allows companies to offer more products due to decreased tooling costs. Conventional methods used for tooling are costly and a mistake often results in discarding the tools. Rapid tooling allows more customization for product manufacturing since tooling is created at smaller volumes. This has an overall negative effect for mass-production mechanisms. But for companies that are focusing more towards low-volume and customized products, AM offers more flexibility and creativity. Due to rising customization demands by consumers, larger companies with higher production volumes could also use rapid tooling as a mean to cope with consumer demands. Thus, this would require a shift in their business models by making them more consumer-centric rather than a product-centric and mass-production-centric one. However, Rayna and Striukova (2015) underlined that rapid tooling would have a limited impact towards value creation.

Digital Direct Manufacturing

Rayna and Striukova (2015) mentioned that any consumer engaging in a co-creation process with the firms becomes part of the firm's value network. With

consumer involvement into DDM, new business models could emerge accordingly. However, Rayna and Striukova (2015) also stated that large companies could still use mass-manufacturing processes unless consumers bring out high demand for mass-customized products. In this case, business models might have to be adjusted with this demand. Especially in the medical sector, we have seen more consumer engagement since medical products require customization at larger levels than other sectors. With the increased consumer engagement in products such as prosthetics, implants, medicine and organs; value networks will be significantly enhanced while value creation could foster with "mass-customization". There is a problem regarding business model changes with DDM. Giving the example of a company that manufactures prosthetic legs, with AM and DDM, the company would still be producing prosthetic legs. Therefore, a total business model change is not expected. However, increased consumer engagement could result in alterations of business models to cope with increasing customization demands and the evolution of other companies and overall prosthetic market with DDM. Thus, DDM is a more disruptive level of AM developments that has the capability to change company behavior and consumer engagement levels. Rayna and Struikova (2015) stated that DDM enables to bring crowdsourcing paradigm to the realm of manufacturing. This directly effects the value networks of businesses. Previously, crowdsourcing was used to support ideas and designs. However, DDM allows crowdsourcing to become an important asset to directly influence manufacturing phases. This could allow companies to use AM as an asset that could be integrated into the business model (Rayna and Struikova, 2015).

For the aerospace industry, value proposition, value creation, value capture and value delivery would see important changes. DDM already started to shape a decentralized distribution and production mechanism for the aerospace industry. With the ability to produce parts and components on-demand and on-site, economical benefits are expected to be significant. Already, companies like Boeing and Airbus are researching such possibilities. Through distributed production abilities by DDM, AM applications would make maintenance and repairs of aircraft easier and faster. Therefore, cost-efficiency and time-efficiency would be achieved due to reduced dependence on logistics, large inventories and product availability. This is expected to change current business models, therefore create a disruption for the aerospace industry since business models are already established accordingly with conventional manufacturing and distribution methods.

Home Fabrication

As the fourth phase of AM technologies, home fabrication offers a new dimension for manufacturers and consumers. With the increased proliferation of home printers, consumers now have the ability to print their own products directly, or download digital designs of specific products of companies to print them at home. This brings a whole new dimension for the concept of manufacturing since the traditional concept of the production is challenged with home fabrication. Coupled with the decentralization of production, home fabrication proves that AM is bringing disruptiveness to the overall manufacturing industry.

In the case of home fabrication, consumers' role in the production processes will be entirely different compared to the current production and distribution models. With increased digitalization of production, any person with a 3D printer could buy digital plans and manufacture products at home as the technology allows people to do so in terms of material availability, size of the product and complexity of the product. Rayna and Striukova (2015) stated that companies might have to completely change their revenue model and move towards more added-value products or derive revenue from complementary services as home printing becomes widespread in line with developments of the capabilities of 3D printers. The Economist (2012) discussed about the "third industrial revolution" and its linkages to 3D printing. The Economist (2012) added that with the digitalization trends in manufacturing, it is now possible to print any product in a garage in the US, or in a tribal village somewhere in Africa. With dependence on digital designs instead of centrally manufactured goods, people will have the flexibility to create their product with customizations they wish for. Rayna and Struikova (2015) stated that crowdsourcing and mass-customizations would be applicable in home fabrication just as DDM. With triggered value creating and value proposition effects, more 3DP adoption for consumers is expected. Rayna and Struikova (2015) also added that effects of home fabrication towards value capture would result in changes of cost structure. Reason to that is the consumer's bearing of manufacturing and distribution costs. This is definitely beneficial for both consumers and companies. With decreased dependence on a centralized mass-production scheme, costs are relatively decreased in terms of manufacturing costs and distribution costs. In this case, businesses' focus would be towards product design and technical support for home fabricators. This trend was present before 3DP entered into consumer market with the advances in internet and limited customization preferences given to consumers for specific products. AM is expected to take this a step forward. Rayna and Struikova (2015) added that companies may have to change

their revenue model completely by moving towards added-value products. One thing Rayna and Struikova mentioned was the inability to print high-tech devices, thus they would be out of the scale of added-value products by companies. However, recent developments have shown that AM has acquired the capability to directly print electronics into products and use conductive materials as input.

In our case, the medical sector is expected to be further effected by home fabrication capabilities. Adding to our further findings in Section 6 for sustainability results, business models of the medical sector are already being disrupted by AM technologies. Home fabrication would allow companies to rethink their business models. By giving the ability to consumers directly print their own products according to their needs is a huge benefit. Given the waiting times for prosthetics globally — especially in the developing world—, this could result in better treatment and integration of people that are in need for prosthetics. This would not only reduce costs, but also create value networks that are inclusive towards consumers. Innovation benefits would be increased, thus adding more value creation through value networks. This would eventually change value proposition of medical sector through increased service offerings and pricing models since customization is taken at the core. Finally, value capture of the medical sector can be altered through changing revenue model since revenues would be focused towards digital design sales and technical assistance.

In the case of aerospace industry, home fabrication is not expected to bring much changes since the consumers of the aerospace industry are civil aviation, governments and military. However, together with the DDM, value creation, value proposition, value delivery and value capture is expected to change at a broader level rather than just home fabrication as we discussed it in DDM section before.

4.3.2 Decentralized Production

One of the most disruptive properties brought by AM to the overall global manufacturing scheme is undoubtedly the decentralization of production. With the abilities to produce components at homes and/or local production centers, the shift is occurring from central production spots to a globally distributed production spots. Apart from industry applications we have mentioned during the business models discussions in this section, the social dimension of the decentralized production also draws attention. One of the examples of the social effects of decentralized production brought by AM is growing “3DP networks”. 3D Hubs is an online platform linking 3D printer owners with consumers around the globe. They currently operate around

25.000 printers worldwide and offer localized production with 3D printers for millions of people with a rapidly growing network (Despierre and Ford, 2016). Lawson (2015) conducted an interview with Bram de Zwart —owner of 3D Hubs— in her article. In this interview, Zwart mentioned some of the sustainability outcomes of 3D printers and also touched upon the future of retail with emerging 3DP technology. She added that Zwart began working in the 3DP industry with the goal of making manufacturing more sustainable and local. With the creation of 3D Hubs, Zwart currently offers access to a 3D printer for over one billion people around the globe within 10 miles of their home. On the future of retail —also connects to sustainability—, Zwart gave Lawson the example of print+ headphones initiative. With “print+ headphones”, people could download digital blueprints of the headphones, design it accordingly (in terms of color) and then bring the design to a 3D Hubs printer or another local printer; and then simply print it. Zwart also added that the company is sending necessary hardware that is not available through 3D printing (cables and ear pads), therefore giving the customer chance to assemble all the parts without the necessity of centralized production and shipment costs (Lawson, 2015). This initiative towards decentralizing production is a very good example of coping logistical costs of centralized production, as well as the time required for the customer to receive the product. It is also worth mentioning here that with 3DP, production not only localizes, but also generates a considerable amount of waste reduction. If the production took place in a factory with a centralized manner and traditional methods of manufacturing, benefits of 3DP would be dismissed. Therefore, decentralized production is a highly sustainable option for manufacturing that comes with 3DP. One idea sparks here is that with more and more initiatives like “print+ headphones”, more products could be decentralized and customized. From the customer perspective, this gives the customer a choice to personalize items and significantly reduce waiting times. From the business perspective, this cuts many expenses of centralized manufacturing and logistics expenses; while also contributing to overall costs of production in terms of raw material usage, energy usage and waste reduction. Also, this brings additional value creations and value networks between consumers and companies as we discussed in business models part of this section. This is a win-win game for both businesses and customers, and there is no obstacle for other companies to implement similar strategies for specific products that could be printed through 3D printers.

4.3.3 AM Adoption's Effects on Supply Chains

Barz et. al (2016, p.2) suggested that with the reduction of raw material input to production, this would effect the quantity of raw material transportation to

manufacturers. Considering the fact that additively manufactured products are lighter than conventionally manufactured products, transportation quantity of finished products and goods are also expected to decrease. This is a direct result of AM adoption into production schemes. There are also indirect effects of AM towards supply chains. With increasing amounts of 3DP communities such as 3D Hubs, supply chains could be further effected by AM technologies. With the production being shifted from central locations to decentralized hubs and home fabrication ability given to consumers, supply chains also need to adapt themselves towards this momentum of change.

In case of a localized and decentralized production, global supply chains' and routes' significance could be effected. Therefore, local-centric and decentralized supply chains would be gaining more significance. Examples we have given in the aerospace and medical industries are pointing such changes. With the ability to instantly repair and maintain aircrafts locally, need for spare parts transportation would be obsolete. Therefore, logistics sector needs to develop strategies to adapt it better towards these "local production hubs" for the aerospace industry. Additionally, Barz et al. (2016, p. 13) indicated that lesser material inputs in the aerospace industry are effecting "buy-to-fly" ratios, causing additional transportation reductions for raw materials to the industry.

The medical sector has already started to offer consumers to fabricate available products at homes, hospitals and clinics. With the developments we stated in Section 4, we have seen that the consumers now acquired the capability to manufacture their own prosthetics with the help of 3DP technology. Doctors can now produce drugs on site according to NUS. Developing nations are also expected to utilize the local production capabilities with AM, especially for medical products. This would decrease dependence on imports from developed nations and other global production hubs for specific products. Therefore, transportation of these products is expected to decrease, thus effecting supply chains' established distribution models. Organ transportation is also among the effected methods. Recent developments indicated that soon, hospitals can produce organs on-demand and on-site. This would decrease the need for organ donors and demand for the transportation of donated organs from one place to another.

5. Disruptiveness of AM

Given the fact that AM has the potential to change business models, logistics and consumer behavior; AM brings together a level of disruption towards the established business models, supply chains, manufacturing schemes, consumer behavior and established markets. In this section, we have applied our framework to the aerospace and medical industries.

Starting with the aerospace industry, we have seen that AM effects businesses in various levels of market and start to increase its market volume each year. Constant developments in the technology and the innovation momentum makes AM adequate for a foothold in various levels of the market. These developments indicate that performance of AM technologies is on the constant rise with more affordable methods and machines being introduced to the market. R&D phases are feasible and well executed but there were not any data available to suggest that R&D is affordable at the moment. Looking at the other favorable indicators, AM has managed to acquire environment-friendly properties with reduced material usage, reduced waste generation and overall energy efficiency during the production phase and life cycle of the products in terms of fuel efficiency. With the ability to create new designs that incorporate biomimicry examples have made additively manufactured products stronger and lighter. These designs were not available with conventional methods, thus proves that AM enables new products to be manufactured. Additionally, we have seen that the AM is both has disruptive and sustaining properties together. These are due to the integration of AM into the established manufacturing methods. Currently, it was not observed that there is a specific line of production just for AM. This creates a blowback for the full disruption by AM. With the fuse of AM and conventional methods, it was observed that hybrid manufacturing is what makes the current overview of the manufacturing in the aerospace industry. Business models of today are mostly towards an AM integration rather than a full adoption by removing old methods. Still, AM has shown disruptive behavior as the drivers were explained in detail at Appendix I. Below, we present our results of the aerospace industry with our disruptive innovation framework:

Drivers	YES	NO
MARKET POSITIONING		
Viable business in the low-end market	5	
Viable business in a new, niche market	5	

Drivers	YES	NO
Are incumbents in the main-stream market willing to run away or ignore the initial disruptors?	1	4
Is the market share of the disruptor at a constant growth?	4	1
TECHNOLOGY		
Adequate for a foothold in the low-end market	5	0
Adequate for a foothold in a new, niche market	5	0
Could be further improved in performance and price/performance	5	0
R&D needed to improve the disruptive technology is feasible, affordable and well executed	4	1
OTHER FAVORABLE DRIVERS		
Favorable life-style changes	N/A	N/A
Environment-friendly properties	5	0
Ability to produce products that were unavailable with previous technologies	5	0

Figure 5.1: Disruptive Innovation Framework for the Aerospace Industry

For the medical industry, we weren't able to acquire data in terms of market developments as we explained in Section 3. Additionally, environmental effects of the AM were not discussed by previous researches. Also, there were no available data to support environmental benefits of AM in the medical sector. Compared to the aerospace industry, the level of AM integration creates more disruption for the overall medical industry manufacturing. Due to the ability of AM to produce almost all products with better performance outputs, its disruption is having a larger effect. Hybridization was not observed in the industry, while business models have evolved into a more AM adoption direction. Still, there is no wide AM adoption. Therefore, the current impact of AM in the medical industry is also both disruptive and sustaining. More details were given in Appendix II. Below, we present our results of the medical industry with our disruptive innovation framework:

Drivers	YES	NO
MARKET POSITIONING		

Drivers	YES	NO
Viable business in the low-end market	3	2
Viable business in a new, niche market	3	2
Are incumbents in the main-stream market willing to run away or ignore the initial disruptors?	0	5
Is the market share of the disruptor at a constant growth?	N/A	N/A
TECHNOLOGY		
Adequate for a foothold in the low-end market	5	0
Adequate for a foothold in a new, niche market	5	0
Could be further improved in performance and price/performance	5	0
R&D needed to improve the disruptive technology is feasible, affordable and well executed	5	0
OTHER FAVORABLE DRIVERS		
Favorable life-style changes	5	0
Environment-friendly properties	N/A	N/A
Ability to produce products that were unavailable with previous technologies	5	0

Figure 5.2: Disruptive Innovation Framework for the Medical Industry

5.1 Results

Our framework indicated that there is a 13:1 Yes-No ratio in the aerospace industry. The ratio for the medical industry resulted in 4:1. Giving the rules of our framework, our results indicate that AM is a disruptive innovation for the aerospace and medical industries. The level of disruption from the drivers in the aerospace sector is higher than the medical sector. This could be explained in two ways.

First explanation is that the level of overall benefits of AM in the aerospace sector are higher. Manufacturing costs in the aerospace industry are massive since aircraft and space craft components require high-standard materials. Overall market effects of the adoption of new technology results faster since the aerospace industry has been at the forefront of adopting new technologies as we discussed in Section 4. Some referred the aerospace industry as a trendsetter, thus level of disruption AM brings has shown its effects faster.

Second explanation is the effect of our data and analysis. As we mentioned, we could not gather data for environmental effects and market share of the medical sector. These are important indicators to consider while adopting a new technology. We have seen that further research is needed to study such effects in the medical sector with AM adoption.

However, AM still holds the potential to replace conventional manufacturing methods in the medical industry due to small-scale and customized products. Currently, there is no evidence suggesting that the AM is replacing the old methods. However, AM has already started to disrupt the current market in the medical sector due to its performance outputs. By looking at the current and the framework, AM of today has disrupted both industries while being kept at a relatively sustaining level as an innovation.

6. AM and Sustainability

Ford and Despiesse (2016) stated that compared to the traditional methods of production, AM results in less waste and has the potential to decouple economic and social value creation from the environmental impact of business activities. Ford and Despiesse (2016) also highlighted three sustainability benefits of AM:

Improved Resource Efficiency: improvements can be realized in both production and use phases as manufacturing processes and products can be redesigned for AM.

Extended product life: Achieved through technical approaches such as repairs, remanufacture and refurbishment, and more sustainable socio-economic patterns such as stronger person-product affinities and closer relationships between producers and consumers.

Reconfigured value chains: shorter and simpler supply chains, more localized production, innovative distribution models and new collaborations (Ford and Despiesse, 2016).

By looking at three sustainability benefits highlighted by Ford and Despiesse, we also managed to come up with similar results in terms of improved resource efficiency and extended product life with better life cycles of additively manufactured products. Our findings in this research suggest that AM is expected to bring waste reduction, material input reduction, cost-effective production, faster production and limited energy efficiency due to the current status of the technology. In this section, we have described our findings in detail regarding sustainability contributions of AM in the aerospace and medical industry. By looking at the current sustainability contributions and future sustainability contributions of AM in the given sectors, we have managed to reach mostly qualitative conclusions while adding useful data for limited quantitative conclusions.

ECONOMICAL	ENVIRONMENTAL	SOCIAL
Material Efficiency (Raw Material Input)	Energy Efficiency (Production Energy Input + Fuel Consumption)	Localization and Inclusion (3DP Communities, decentralized production)
Reduced Production Costs (Energy Efficiency + Material Efficiency + Production Speed)	Carbon dioxide Emissions Reduction (Transportation + Product Life Cycle Improvement)	Increased Life Quality (Medical Products, On-Demand Organs, Local Production)
Product Life Cycle Improvements	Reduced Waste Generation	Home Fabrication Capabilities
Decentralized Production (DDM + Home Fabrication		

Figure 6.1: Overall Current Additive Manufacturing Contributions towards Sustainability

6.1 Current Effects of AM towards Economical and Environmental Sustainability

Economical and Environmental Sustainability

Exploring AM through the lens of industrial sustainability provides a more comprehensive understanding of AM for improving the sustainability of industrial systems with a complex-large number of actors, interlinked value chains, services, money and exchanging information (Ford and Despiesse, 2016). From the industrial point of view, what we see is concentrated focus towards economical benefits. Since businesses' main focus is to maximize profit, economical view towards sustainability is understandable. One of the main characteristics of AM is that, it incorporates economical benefits with environmental benefits. Environmental benefits are perceived as a side effect of AM in aerospace industry due to prioritization of economical benefits over environmental benefits (Despiesse and Ford, 2016). But these benefits of waste reduction and material usage efficiency would be an important contribution towards sustainability due to their after effects of lightweight products and fuel/energy efficiency of the end-products' life cycle. Sustainability contributions of AM are generating less waste during production, optimization of geometries and resulting in lightweight products, reduction of transportation needs in supply chain and ability to create spare parts on-demand resulting in less inventory waste (Chen et al. and Mani et al. as cited in Despiesse and Ford, 2016). According to Gebler et al. (2014), lightweight design features of AM could result in carbon dioxide reductions of up to 75% by 2025. With the optimization of AM in aerospace and automotive industries, Gebler et al. (2014) stated that 63% savings in terms of energy usage and carbon dioxide emissions can also be reached with additively manufactured products. Sreenivasan and Bourell (as cited in Fraizer, 2014) stated in their study that SLS method is an energy efficient and sustainable production method due to energy input optimizations during the production. Petrovic et al. mentioned 40% reduction in raw material-related waste could be avoided through 3DP and 95-98% unfused raw materials can be reused (as cited in Gebler et al., 2014). Usage of recycled material in AM is also an important environmental input that contributes to sustainability. Despiesse and Ford (2016) mentioned two new methods called fused deposition modelling (FDM) which enables the usage of the waste plastic filament and EKOCYCLE Cube home 3D printer uses recycled polyethylene terephthalate (rPET). Such methods could be utilized to use waste plastic and turning it into usable products. Despiesse and Ford (2016) also mentioned the collaboration between 3DS and the Coca-Cola Company to reuse waste plastic bottles from the waste stream.

AM is expected to become more cost-effective as larger production volumes become more economically feasible than its current levels. This may lead to mass-production utilizations of AM and leading to higher sustainability contributions (Despierre and Ford, 2016). But first, technology needs to reach a level of maturity by enabling multi-material printing, hybridization with traditional production methods, cheaper devices for printing, increased material quality, decreased human interference and increased automation, ability to produce larger components, higher energy efficiency with metal materials. Redesigning current products for making them suitable for AM would result in an optimum strength-to-weight ratio.

By looking at the aerospace industry, we have seen that there is a momentum towards considerable economical and environmental benefits due to AM adoption. Cases we studied regarding engine production, satellite production and aircraft component manufacturing; we have seen that AM brings a lot of economical and environmental contributions to the sector. With faster production times, longer life cycle of products and energy/fuel efficiency of the final products, AM is expected to proliferate into more applications in the aerospace sector.

Even though we have reached to different numbers of material efficiency in our cases, it is safe to state that AM adoption results in optimization of raw material input into production. Looking at the buy-to-fly ratios in the aerospace sectors from figures of 4:1-20:1 with conventional manufacturing methods, AM allows this ratio to be reduced to almost 1:1 in most of our cases. This is due to the properties of AM technologies since in AM, only the amount of material that is required to build a product is required as input while conventional methods such as casting, milling and CNC results in higher waste generations since excess material is thrown away. Even though there have been improvements for conventional methods in recent years for waste reduction and recyclability, AM still holds the upper hand. Therefore, cost-effectiveness in terms of raw material acquisition is reached by the sector while huge amounts of waste reduction of up to 95% contributes to the environmental benefits. Given these properties of AM technology and the momentum of further integration AM into manufacturing of aerospace products, AM is a sustainable option for the industry for economical and environmental pillars of sustainability.

As we stated before, there aren't enough data to suggest the environmental contributions of AM in the medical sector. However, we have seen a number of

economical benefits in the sector with AM adoption. In terms of material efficiency, we have seen that AM allows less material to be used in medical products. With increased durability and decreased weight of the prosthetics and implants, costs have been significantly reduced compared to the conventional production methods. With more AM integration to the medical sector, we are expecting more cost-reductions and waste reductions. Other benefits AM is expected to bring to the medical sector is the delivery time reductions and production time reductions. With faster production offered by AM, medical sector is now able to produce implants and prosthetics faster compared to conventional production methods. With the ability given to consumers for producing their own prosthetics at home due to digital manufacturing capabilities and material availability for home printers, logistics costs for delivering prosthetics worldwide is expected to decrease, therefore resulting in cost reductions for logistics in medical sector while reducing fuel usage and carbon dioxide emissions during the delivery of such products to consumers. This is again an interlinked economical-environmental sustainability contribution of AM in medical sector.

Social Dimension of Sustainability

Social pillar of sustainability is also supported by AM technologies. In the medical sector, we are expecting a social result in terms of medical and biomedical component deliveries. With decentralized production capabilities, doctors and hospitals are now able to produce prosthetics, implants, organs and medicine with AM technology. This may overall have an effect on the people by decreasing the amount of waiting time for organ transplants and prosthetics; therefore saving and improving millions of lives globally. Especially, the effects of these developments in the developing regions are expected to be huge. With decreasing costs of prosthetics made with AM, there is hope for amputees in relatively poor regions. Open Bionics developed a 3D-printed prosthetic arm that costs only 5% of the average prosthetic arms and is produced only in 3 days. Open Bionics stated that they made their technique an open source so that anyone can use it to create prosthetic arms for needy people. Connected to the localization of AM and increasing 3D printer hubs, this is a promising breakthrough. By allowing millions of amputated people to have prosthetics, AM is expected to increase overall life quality in developing and remote regions. This is achievable with decreased costs of prosthetic production and ability to have a decentralized manufacturing scheme thanks to AM technology. By allowing medical centers and NGOs in these regions to produce and distribute prosthetics and implants, thousands of lives may be saved. With prosthetics, people can live better lives and will be able to do things that were previously not possible due to their

amputation such as working and participating in social activities. The overall contribution of these developments might foster sustainable development in the region by allowing to work again and take care of their families. Economical benefits of the decentralized production scheme also have the possibility to create labor in remote regions with these initiatives.

Looking at the broader effects of AM towards social dimension of sustainability, emerging “3DP communities” are changing the landscape. The Economist (2012) mentioned a social dimension of rising 3D printer usage by expecting “Facebook-like communities” to allow people to share designs and printers for consumer usage. Networks such as 3D Hubs of today are a good example of such movement of increasing 3D printing communities that allow everyone to operate a 3D printer if a hub is available to their homes. Apart from 3DP communities, AM also offers more possibilities for consumers under “home fabrication” capabilities (Rayna and Striukova, 2015). This is expected to bring a new dimension towards broader manufacturing industry since it allows people to create their own products at their homes with customization benefits. As it connects back to the medical industry, the ability to print medical products at home is bringing a new social dimension for the medical industry and people interactions. Overall, this would bring a new digital market for AM designs allowing people to buy and download production designs such as CAD/CAM and manufacture what they need at home. Social implications of this new market will be more consumer involvement in the production schemes of corporations, therefore making consumers to effectively engage with business models as discussed before at section 4. For the automation brought by AM, we have encountered with controversial results. For the future of AM and social dimension of sustainability, we have discussed automation more in detail. For the current social implications, we have seen positive effects. Despiesse and Ford (2016) stated that with decreased need for human interference to AM machines, workers’ health is improved by avoiding long-term exposure to harsh and potentially hazardous environments. Our findings also suggested lesser human interference during the production since AM machines require little-to-no operator interference during the production since after digital design is uploaded, machines do the rest themselves.

6.2 Future of AM and Sustainability

Economical and Environmental Sustainability

By looking at the current momentum of development in the AM technologies, it is expected that AM would find itself more applications in the aerospace and medical sectors. As we will discuss in this section, benefits of AM adoption by 2025 in terms of

cost reductions, energy efficiency and mitigating carbon dioxide emissions are high. Aligned with the current developments in the industries, better AM products with better properties are expected such as increased energy efficiency, multi-material printing, electronics printing and mass-production capabilities. With the ability to instantly produce required spare parts and components for aircraft, maintenance costs and waiting times for deliveries are expected to drop. With cheaper, lighter and more durable products, the overall fuel efficiency of aircrafts is expected to be increased. On the satellite production, more AM integration into the production means lighter and more durable satellites. Effects of these developments would be lesser launch costs and fewer fuel demands to place satellites into orbit. With increased product life cycle, economical benefits of the future aircraft and satellites would be far more advanced compared to the current levels. It is obvious that these benefits are attracting more companies to adopt AM technologies today. With the momentum of changes and improvements in AM, more aerospace companies would incorporate AM technology. This may be solely AM-based production or hybridization of the improved conventional methods and AM technologies. Such distinction depends on the development of AM technologies. If AM enables mass-production while being cost-effective for the production of established products, AM holds the potential to be the manufacturing method of the future. Despiessie and Ford (2016) stated that hybrid manufacturing processes offer a wide range of advantages such as improved finish quality, shorter production time and reduced tool wear. With this hybridization, more sustainability contributions are achievable in terms of economical and environmental benefits. It is still not clear whether a hybrid or AM-only manufacturing scheme will thrive in the future. Current situation suggests a hybrid manufacturing. Considering the fact that AM technologies are on a constant pace of development, otherwise is also possible.

Overall, life cycle of products would be improved with AM. Adoption of AM could lead to savings of US\$ 593 billion by 2025 with shorter supply chains, less material usage and end-product energy efficiency (Gebler et al., 2014). This range is determined by the scenarios Gebler et al. (2014) created and depends to low-adoption scenarios and high-adoption scenarios. As we mentioned in Section 3 of our research, we will be using maximum benefits from all indicators. Aerospace and medical sectors consist an important share in these savings. Aerospace industry's share in the total savings are 33% on fuel demands followed by 14% during the production of aerospace products. 15% of total savings are related to production in the medical sector.

Data given by Gebler et al. (2014) in terms of total primary energy supply (TPES) savings and total life cycle carbon dioxide emissions savings is accepted as 9.30EJ globally by 2025. Within TPES total savings, aerospace again takes the lead. In terms of aerospace fuel demands, sector's contribution towards TPES total savings are 35%, while aerospace production is at 19%. Medical sector also consists 19% share in total TPES savings.

Finally, data given by Gebler et al. (2014) regarding total life cycle carbon dioxide emissions savings is accepted as 525.5Mt by 2025. Again, we are seeing important contributions by the aerospace industry and medical industry. Aerospace fuel demands consist 35% share, aerospace production consists 19% and medical sector consist 19% shares in the total carbon dioxide emissions reductions.

Looking at the broader manufacturing scheme, we will be witnessing a new market emerging for digital designs that allows people to create their own products with home fabrication. Home fabrication is available as of today with limited applications as we mentioned 3D Hubs example. However, with increasing demands for product customization, we will be seeing an expanding market that includes designs of products of which are not available today for home fabricators. Aligned with the increasing capabilities of 3D printers, this new digital market will bring additional value for companies in terms of profits. With the ability to leave consumers to produce their own small-scale products, companies would enjoy the benefits of reduced logistics costs and large inventory maintenance costs. It is not feasible to predict the value and volume of such market today. Therefore, our research is not giving any indicators on how this market may expand. However, emergence of such market is inevitable. Overall sustainability benefits of this market would be cost benefits for companies and reduced logistics needs resulting in less carbon dioxide emissions related to the transportation of such products. Another development that could potentially contribute to the mitigation of carbon dioxide emissions is a recent novel method discovered by University of California at Los Angeles (UCLA) researchers. UCLA researches managed to turn carbon dioxide into sustainable concrete with this novel method. Foulsham (2016) from UCLA stated that with this new technology, carbon dioxide pollution could be turned into a usable concrete, thus opening a new frontier for fight against climate change. Interdisciplinary research team from UCLA managed to create what they called "CO₂NCRETE" using captured carbon from greenhouse gas sources and turning them into concrete using 3D printers. With up-cycling carbon dioxide into this beneficial material, carbon capturing processes could

be taken into a whole new level, thus enabling new policy options for mitigating climate change with beneficial byproducts during carbon capturing process (Foulsham, 2016). Coupled with increasing housing demands due to rapid urbanization and increasing global population, benefits are not limited to carbon dioxide emissions only. If this method proves to be beneficial in terms of cost-effectiveness, a new line of business that supports economical, environmental and social dimensions of sustainability simultaneously would emerge.

Another economical aspect of digitalization trends in manufacturing is the shift of production from low-wage countries to consumer countries. The Economist (2012) stated that with increasing AM and automation in factories, human labor will not be needed as before, thus, causing a shift of production from developing countries back to the developed ones. However, it is also worth mentioning here that with AM and 3DP, decentralization of production might still allow local communities and developing countries to take back the production and increase life quality in remote regions as we mentioned in the previous section regarding social dimension of sustainability. Still, it is also worth mentioning that The Boston Consulting Company expects goods and services of transportation, computers, fabricated metals and machinery will be shifted back to the US from China at a volume of 10-30% of the current imports (The Economist, 2012). This is expected to boost American economical input by US\$20-55 billion by 2020.

Social Dimension of Sustainability

Just as it is expected from the AM to give social contributions currently, future also holds many possibilities and challenges ahead for AM. Considering the continuation of the current momentum of innovation and consumer integration into the production, AM of the near future is expected to continue to expand these features.

Medical sector again promises social contributions by new innovations. Looking back at 3D printed artificial ovaries we have discussed in Section 4, we are expecting this technology to be available for humans after initial clinical tests are done and technology gets approval for human applications. This could allow infertile women to have children again, thus resulting in a social contribution by AM technologies.

As we discussed in the previous section regarding automation brought by AM, it is expected to be discussed extensively in the following years. Due to reduced dependence on human labor, humans may lose their jobs to the machines. This is

not only an aftereffect of AM, but with evolving conventional production methods, the same problem arises. This would have a huge effect on the society since much of the blue collar jobs will be threatened by being replaced by machines. Many industry leaders expect the automation to take the jobs from people. Since product designs and programming of these machines would be more important, dependence on engineers, designers and IT personnel would eventually increase. One conflictual finding we have acquired here is the expected production shift from developing nations to developed nations. If the expected shift occurs, then the scenario of decreasing blue collar dependence would be relevant. However, considering the fact that AM is also expected to bring decentralized production schemes, this would eventually need more local engagement and therefore, resulting in increased economical prosperity for developing nations. At the moment, sustainable development trends in the social dimension of sustainability are not clear. Thus, prediction of the near future was not possible in our research. Due to this research's limitations, only insights and suggestions were given. Therefore, there is a need for further research to study social effects of AM for the current time and near future.

6.3 Challenges and Threats Ahead of AM

Oropallo & Piegl (2015) underlined the importance of addressing the challenges ahead of AM by giving the example of the lack of attention towards the problems of the earlier technologies such as CAD/CAM. Oropallo & Piegl (2015) stated that this lack of attention resulted in decades of further improvement of the technology, therefore preventing wide adoption by the industry. Without addressing critical challenges ahead of AM, technology's ability to reach a mature stage might be jeopardized as well as reducing the attractiveness of AM through the lenses of the industry.

By looking at the overall incompetences of the AM technologies of today, we have identified a number of challenges which connects to Oropallo & Piegl's research. Choosing suitable printing method is one of the key issues since it also effects the final product due to different processes of the production phase. This leads to the challenge of better education of manufacturers in terms of AM capabilities. Oropallo & Piegl (2015) indicated that all of the methods have their advantages and disadvantages, but choosing the right method is crucial.

Another important challenge is the need for multi-material printing capabilities of AM technologies. Oropallo & Piegl (2015) mentioned that 3D-printed objects are referred as homogeneous and heterogeneous parts. In homogeneous parts, a single

material is used for the production of such product. But for the heterogeneous parts, multiple materials are required for the production. Problems deriving from heterogeneous products are mainly the compatibility of printers to handle different materials and the proper interaction of different materials in the final product. Oropallo & Piegl (2015) stated that there are many challenges for multi-material applications such as the complex data leading to complex production. Since most of the production in the aerospace and medical industries are rather complex, AM needs to adapt itself to meet the demands of the industry. Recent developments have shown promising results in terms of multi-material printing. With increasing multi-material printing capabilities, factors of production such as production speed and product complexity are being addressed. With the inclusion of electronics into printable materials, multi-material printing offers significant advantages. However, prices of these printers are expensive at the moment. Thus, disabling SMEs and consumers to benefit from such capabilities. In order to better incorporate AM to consumers, small businesses and enterprises with increasing demands towards DDM and home fabrication capabilities; AM could reach to a new market level, thus increasing its disruptiveness and competitiveness to conventional methods.

Despisse and Ford (2016) also mentioned challenges ahead of AM. Firstly, designers and engineers perceive AM as a tool for rapid prototyping rather than direct component and product manufacture due to limited applications. This is currently being resolved with novel methods and almost daily occurring innovations. With the rise of multi-material printers, complex products are becoming easier to produce with AM. Second challenge mentioned by Despisse and Ford (2016) is the performance of AM technologies. They have mentioned microelectronics cannot be embedded into products with AM. They have stated that AM needs to improve to allow integration of such components into products. However, recent developments indicate that various 3DP methods are now being used to incorporate microelectronics by using conductive materials. Then, placing electronics into already laid layers and building more layers upon such components, thus resulting in a fully operational electronic component made with AM. Aerosol Jet by OPTOMECH is one example of 3D printers that incorporates this capability. With the developments of nanotechnology, material availability is expected to result in better electronics printing. New materials such as carbon nanotubes and nanoparticles are suitable candidates to be considered for additively manufactured electronics components.

By some, AM is considered as a direct substitute for traditional manufacturing processes. However, primary economic benefits of AM lies in customized single or small batches of goods. In its current manifestation, AM cannot be a direct substitute for the whole manufacturing sector. However, AM could be a substitute for some manufacturers dealing with small-scale customized production (Despisesse and Ford, 2016, p. 1581). It is important to add here that if AM reaches technological maturity with constant innovations connected to multi-material printing and mass-production capability, then it would be considered as a substitute for conventional methods or a transition for manufacturing by many —if not most— manufacturers.

It is still unclear that whether AM adoption would result in a shift of production from developing nations with comparably cheaper labor to technologically advanced consumer nations. If such transition occurs, the effects would be highly negative for developing nations. In case of a wide AM adoption by various industries coupled with automation, developing nations could lose their advantage of cheaper labor for manufacturing sector. This would result in desirable economical contributions for multinational companies. However, side effects would negatively influence development figures of those nations left behind. Through the lens of economical and social sustainability, this would overall reduce competencies of developing nations. Therefore, resulting in a massive blowback for global sustainable development. However, decentralization brought by AM technologies offers different results than the previous scenario. Decentralization could be the solution to prevent such transition. Therefore, ensuring that sustainable development is contributed in developing nations, rural areas and remote regions.

Intellectual Property (IP) is another challenge ahead of AM adoption and proliferation. With the digitalization of designs and productions, problems arise in terms of IP. Designs could be subjected to industrial espionage and find their ways to blackmarkets. Digital design piracy is another concern for companies before deciding to adopt AM. With the decentralization of production, mistreatment of IP can also be encountered. Without a legal mechanism to take these threats into consideration, AM adoption could be slowed down. Therefore, companies and governments are encouraged to take precautions towards these potential developments.

TIME	ECONOMICAL	ENVIRONMENTAL	SOCIAL
Current		Lack of Evidence Towards Hazardous Effects of AM in Factories for Workers	
Current + Future	Transition from Conventional Methods to AM (Costs of Upgrading Factories + Discarding Old Machinery)		Job Losses (Workers With No Experience/ Training of AM + Automation)
Current + Future	Automation (Universal Minimum Wage Problems)		
Future	Potential Shift of Production from Developing Nations to Develop Nations (Resulting in Economical Stagnation in Developing Nations)		Potential Shift of Production from Developing Nations to Develop Nations
Future	Adaptation of an Established Transportation Sector to AM's Effects		

Figure 6.2: Overall Current and Future Sustainability Threats of Additive Manufacturing

7. Conclusion

In this thesis, we have studied the effects of AM integration to the aerospace and medical industries. After we looked at the developments of the technology in respective sectors, we looked upon AM adoption's effects in terms of business model changes, decentralization trends and supply chain changes. Then, we used our framework to determine if AM is disrupting our focus industries. After we gathered our results, we have looked at the sustainability effects of the AM adoption in terms of economical, environmental and social pillars of sustainability at current and future levels.

Our main research question, "Does AM contribute to sustainability in terms of economical, environmental and social dimensions of sustainability in the aerospace and medical industries?" was answered accordingly by summarizing our findings. We have seen that AM adoption results in a number of benefits for each industry. The aerospace industry has shown that AM adoption leads to economical benefits deriving from increased material efficiency, reduced waste generation and lightweight products. Environmental benefits were seen as reduced raw material usage, reduced waste generation and energy efficiency for the production phase and life cycle of the final products with reduced fuel consumption. Our results for economical contributions of AM the medical sector shown that with reduced raw material input, costs were reduced significantly. This resulted in affordable products for the consumers while making production more affordable for the businesses. Social effects of the AM adoption has shown that consumer participation into the production allows people to manufacture their own medical components with the possibilities deriving from DDM and home fabricating. With decentralized production, AM offers medical products to be delivered to remote and developing nations with affordable costs. This creates social changes such as better treatment of people in need for prosthetics and implants. Overall AM adoption with decentralized production enables remote and developing communities to produce products and generate services that could result in increased life quality in these regions. With decentralized production schemes and environmental benefits of additively manufactured products, sustainable development in the developing nations as well as developed nations can be contributed.

For the sub-question "Is additive manufacturing disrupting the aerospace industry and the medical industry?", our framework suggested that AM possesses characteristics of disruptive innovation for the aerospace and medical industries. With the changes AM brings in terms of market positioning, technology and other favorable

drivers; disruption of the conventional manufacturing scheme is occurring. This disruption is expected to increase as technology matures and develops to a more desirable stance compared to the conventional methods while also the market share of AM products keep rising.

For the sub-question “What are the possible contributions of additive manufacturing towards sustainability?”, we have observed that AM offers a number of contributions towards economical, environmental and social dimensions of sustainability. As we explained for the results of our main research questions, the results also match this question. Not only the aerospace and medical industries benefit from these, but also other sectors can utilize the benefits of AM such as construction and automotive industry which are also industries causing high carbon dioxide emissions and other environmental impacts. Economic contributions of AM shows effects in the overall business structure and production schemes. Businesses benefit from AM in terms of decentralized production and reduced logistics costs. Production gains the most benefits in terms of economical contributions of AM since material input and waste generation is decreased, resulting in less material costs and waste disposal/recycling costs. Faster production of specific AM-compatible products also creates economical benefits while mass-customization capability gives businesses the ability to satisfy consumer demands. Environmental contributions range from reduced material input to overall energy efficiency both during the production and life cycle of products especially in the aerospace industry. Reduced carbon dioxide emissions generation of additively manufactured products also offer indirect environmental benefits of the AM technology. Coupled with the decentralized production capabilities and reduced transportation needs, AM could be a solution for companies to reduce their environmental impact. Social dimension also benefits from AM adoption especially in the medical industry. Overall, AM at its current stance holds an interesting potential to cope with sustainability issues in various industries.

Sub-question of “What are potential future sustainability contributions and general challenges ahead of additive manufacturing?” also provided a number of results that could help us understand the AM and sustainability effects at a broader sense. Figure 6.2 at Section 6 summarized our findings in a simple table. We have seen that economical threats are mainly towards future challenges. Transition required to adopt AM requires to replace conventional methods and re-design factories accordingly. This creates an economical cost depending on the level of adoption and the volume of production of the businesses. Automation also requires an investment

into this transition since factories with AM require less human interference with the production. Before adopting AM, these costs need to be carefully analyzed and compared with the benefits of AM adoption. Automation not only creates an economical cost for the businesses, but also a social cost for both businesses and their employees. AM adoption could result in people losing their jobs, thus creating a social problem to be dealt with by not only businesses, but also governments respectively. Adaptation of the transportation with the changes brought by AM also creates risks for the logistics sectors. With production being dependent on the high-tech manufacturing through AM, production could be shifted from developing nations to the developed nations. This creates both economical and social challenges since the global manufacturing is currently focused towards affordable labor offered by developing nations. Without much dependence on the labor with AM, developing nations could lose economic competences and people could face losing their jobs. One environmental problem we observed in this research is the lack of environmental impact studies of AM utilization in the factories. There are no studies or evidence suggesting that AM offers a hazard-free working environment in the factories. Since AM processes are newly proliferating and different methods with different materials also enter into production, it is still unclear if AM has the potential to harm workers.

Overall, AM technologies are offering wide ranges of sustainability benefits for the aerospace and medical industries, as well as a number of potential challenges. With decreased production costs and life cycle improvements of the products, AM adoption to the overall manufacturing industry is picking up. In light of our results, we are expecting more AM integration to the aerospace and medical industries, as well as other industries to follow. This integration and adoption of AM would be more efficient and beneficial if the potential challenges are also addressed as well as the benefits are constantly underlined. Thus, we have identified a number of future research topics with the potential to increase our understanding of AM adoption. These recommendations are deriving not only from our findings in this thesis, but also from the challenges encountered while collecting data from the industry and academia to enrich our findings. *Firstly*, with increasing integration of AM into the aerospace and medical industries, sustainability effects of this integration should be understood in more detail. Case-specific research is needed to provide useable data for specific AM methods in these industries. Future research with detailed data and access to the industry's data would improve our understanding of sustainability outcomes of AM adoption. *Secondly*, the aerospace industry needs to be further studied in terms of energy efficiency of AM adoption during the production phase. *Thirdly*, the medical

sector still lacks data to provide environmental benefits —or threats— of AM adoption and also a valuable market data to study disruption of AM in the medical industry. *Fourthly*, LCA-based studies to understand sustainability effects of additively manufactured products would also contribute to our understanding of sustainability outcomes of AM adoption not only during the production phase, but also usage phases. *Fifthly*, there aren't enough studies to look into IP-related challenges ahead of AM. IP-related challenges holds the potential to disturb economical benefits of AM while creating social problems such as digital design piracy. Further research focusing on resolving current and potential IP issues brought by AM adoption is needed. *Finally*, in order to understand the disruption caused by AM quantitatively, there is a need for further research to acquire data. With comprehensive data from the industries and market developments of AM; results can be improved and disruption that AM causes can be further understood.

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9. Appendix

Appendix I: The Aerospace Industry and Disruptive Innovation Framework

Our findings in the aerospace industry suggested different results compared to the medical industry. By looking at the manufacturing behavior in the aerospace industry, there are no indicators suggesting that the AM is a solely disruptive innovation. As it was mentioned in Section 5, it is possible to see both disruptive and sustaining characteristics. Conventional production market still continues to grow while conventional production still takes the lead at the overall aerospace manufacturing scheme. However, additively manufactured products' performance outputs are suggesting the disruptive potential of AM. Here, we explain how we looked at each criteria with respect to our findings:

1. Viable business in the low-end market: Due to rapid prototyping ability with AM, 3D printers and other AM solutions can be found at lower prices for start-ups, SMEs and large companies. These products that are specifically designed for rapid prototyping are cheaper since they do not require complex features such as multi-material printing and large volume production capabilities. Current AM market since the early 2000s had expanded to a larger volume and keeps expanding with more aerospace investments into AM solutions. Additively manufactured final products are cheaper and faster, therefore, suitable for the low-end market.
2. Viable business in a new, niche market: 3D printer market and AM product market are on a constant rise. This study's findings indicated that companies are acquiring more AM machines each year and increasing their additively manufactured products. The rise of AM machines sold and the volume of this new product market is on a constant rise between 2010-2016. Details could be found in Section 4. Projections suggest that the market would see a double digit-growth for the following years.
3. Are incumbents in the main-stream market willing to run away or ignore the initial disruptors?: No. We are seeing that the AM techniques and conventional manufacturing techniques are both being used by companies. Major aerospace companies are rising their investments into AM solutions while upgrading conventional methods. Instead of ignoring, both manufacturing methods are being used together. Hybridization of manufacturing methods suggests a sustaining effect by the AM.

4. Is the market share of the disruptor at a constant growth?: Yes. Results indicated that AM market for the aerospace is at a constant growth between 2010-2016.
5. Adequate for a foothold in the low-end market: Yes. Decreasing prices of AM machines make them suitable for many businesses due to low costs and many benefits.
6. Adequate for a foothold in a new, niche market: Yes. Advances in the technology make the market dynamic and active. New products enter the market almost daily and sales of AM machines are on a constant rise.
7. Could be further improved in performance and price/performance: Yes. Due to less material input, lower waste generation and energy efficiency; AM offers higher price/performance results. With constant R&D, AM is efficiently improved.
8. R&D needed to improve the disruptive technology is feasible, affordable and well executed: Yes. Multi-material printing, energy efficiency, faster production and incorporation of electronics printing make current AM machines more advanced compared to previous AM machines. R&D investments are on the rise and companies are looking for new advancements each day. Developments in the recent years also improved the AM performance, thus making it ideal for the industry.
9. Favorable life-style changes: No indicators/results suggesting AM offers life style changes in the aerospace industry. Not applicable.
10. Environment-friendly properties: Due to less material input, less waste generation, energy efficiency during the production and life cycle improvements regarding fuel consumption; AM offers environment-friendly products with environment-friendly production methods.
11. Ability to produce products that were unavailable with previous technologies: Due to the ability to create complex geometries and different alloys/mixtures that were previously unavailable, AM offers new ways of production and new final products for the aerospace industry such as titanium powder, new satellite components and aircraft parts.

Appendix II: The Medical Industry and Disruptive Innovation Framework

Our findings in the medical industry were limited due to lack of sources focusing on environmental aspects of production and market share of AM technologies in the medical sector since the data is not publicly available and the industry has different priorities compared to the aerospace industry in terms of economical and environmental dimensions of sustainability. Overall disruption in the medical industry is larger than the aerospace industry. This is due to the AM's capability to replace conventional methods. It was not observed in any case that a hybrid method was utilized. Therefore, the disruption caused by AM in the medical industry is more significant than the aerospace industry. Below, drivers are explained in detail:

1. Viable business in the low-end market: We have seen that AM enables the medical industry to create low-cost products for consumers. Low-costs usually derive from the lower production costs due to AM utilization. These AM machines are relatively cheaper than the conventional methods and even enables home users to create their own products using 3D printers and digital designs from companies. Reduced costs of the established products made a viable business opportunity in the low-end market.
2. Viable business in a new, niche market: AM also creates a new market for itself in the medical sector. Due to first successful usages of AM in the 1990s, a new market has been created for AM for the medical industry. Today, more and more companies invest in AM methods, thus resulting in an increased market activity. However, the market volume data is not available.
3. Are incumbents in the main-stream market willing to run away or ignore the initial disruptors?: It was not observed by any indicator or development suggesting that the AM is being ignored by the established businesses. We have seen that the academia, companies and research institutions have incorporated AM with ease.
4. Is the market share of the disruptor at a constant growth?: Due to no public data for the market share of the AM in this industry, this is not applicable.
5. Adequate for a foothold in the low-end market: Increased AM utilization in the industry indicates that need for low-cost AM machines has increased in recent years. Already, there are many users of these machines in the industry. With the inclusion of home users into the low-end market due to home fabrication properties of AM, it is adequate for a foothold in the low-end market.
6. Adequate for a foothold in a new, niche market: Increased AM adoption gives the possibility to create new products and improves old products in the medical sector.

Investment into AM is high in biomedical, educational and pharmaceutical sectors. There is a dynamic market available for AM.

7. Could be further improved in performance and price/performance: Yes. Production is more cost-efficient compared to the traditional methods. With the introduction of newer machines and techniques, cheaper products are emerging without lacking any performance. Also, production speed improves performance output of the AM machines.
8. R&D needed to improve the disruptive technology is feasible, affordable and well executed: Yes. We have seen that many companies and research institutions invest into AM R&D for the medical industry. Our findings indicate that there is a constant growth in AM capabilities and improvement of the methods.
9. Favorable life-style changes: Inclusion of consumers into production creates new ways of consumer activity. With cheaper prosthetics, more capable implants, organ fabrication and better drugs, people's life-style has already started to change.
10. Environment-friendly properties: Due to lack of environmental data and sector's priorities, this driver is not applicable.
11. Ability to produce products that were unavailable with previous technologies: Yes. Customized medication, prosthetics, organs and other products are available due to AM integration. Shape-shifting multiple-drug medication was not available previously. Also, on-demand and on-site fabrication of organs was made available by AM.

Declaration of Academic Integrity Master SSP Thesis

I, Aican YILDIZALP , hereby declare with relation to my master's thesis "Additive Manufacturing Technologies' Sustainability Contributions in the Aerospace and Medical Industries" that:

I am aware of and have understood the rules and regulations stipulated in the Education and Examination Regulations (EER) of the Master SSP programme regarding fraud and plagiarism;

I am aware of the possible consequences and disciplinary measures in the case of fraud and plagiarism in my Master's thesis;

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I have carefully marked and referenced all direct quotes and references all indirect quotes included in my Master's thesis;

My Master's thesis is an original result of my own work and does not include the work of others except in the case of direct and indirect quotes that are recognizable as such (exception: Master's theses that have been co-authored as requested from and approved by the Examination Committee).

Place

Maastricht, The Netherlands

Date

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Signature

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