Additive Manufacturing (3 D Printing):

Challenges and Opportunities for Large Scale Adoption

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SUBMITTED TO THE MIT SLOAN SCHOOL OF MANAGEMENT

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER IN BUSINESS ADMINISTRATION

AND

MASTER OF SCIENCE IN MANAGEMENT OF TECHNOLOGY

AT THE

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2017

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Submitted to MIT Sloan School of Management

on May 12, 2017 in Partial Fulfillment of the

requirements for the Degree of Master of Business Administration.

ABSTRACT

3D printing (additive manufacturing) has been around for more than 30 years. A lot of technological progress has been made in that time, most recently with new innovations such as metal 3D printing. Although the technology seems to hold a lot of promise, the rate of adoption has not lived up to the hype.

The aim of this thesis is to research what has stopped 3D printing from catching on faster? What factors are hindering large scale adoption for mass production? We apply the "Iterating to Insights" framework to analyze technology limitations, market dynamics, business models and industry structure and to develop strategic insights that are surprising yet compelling. Our end-goal was to develop a set of insights that can be used by an investor in a 3D printing company to evaluate whether an application or market being pursued by a potential investment is worthwhile or not.

Thesis Supervisor: **Duncan Simester**

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ACKNOWLEDGEMENTS

Dedicated to my wife Emilia and my children Ruvarashe and Simbarashe for their support, patience and encouragement during my journey through the Sloan Fellows program.

Tafadzwa A. Magaya

Dedicated to my wife Kavita, and my father Charanjit Roy Jain for their love, support and trust. I also thank my mother Prem Jain and my son Pranav for their immense love which helped me reach this milestone.

Supesh Jain

We are very grateful to our thesis advisor, Professor Duncan Simester for his guidance and support, in navigating through our research. His systematic and focused approach was instrumental in the successful completion of this document. We also thank our SF 17 colleagues Jasjit Makol and Malene Kvist Kristensen for their excellent contributions.

Tafadzwa A. Magaya

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Contents

Background and Objectives

The origins of 3D printing (3DP) can be traced back to 1986, when the first patent was issued to Charles Hull for stereo lithography apparatus (SLA). He was the founder of 3D Systems Corporation (https://www.3dsystems.com/); which remains one of the largest 3D printing companies today.[1]

First commercial sale of 3D printing systems happened in 1988, when 3D Systems sold their first machine, the SLA-1. In the late 80s and in the 90s, new methods such as Selective Laser Sintering (SLA), Fused Deposition Modelling (FDM) and Direct Metal Laser Sintering (DMLS) were introduced. New companies such as STRATASYS and EOS (Germany) emerged as leaders. Throughout the 90s and early 2000s, 3D printing became more widely used in industry and new applications emerged including rapid prototyping, rapid tooling, rapid casting and manufacturing.

The umbrella term “additive manufacturing” gained wider currency in the first decade of the 2000s. As various additive processes matured, it became clear that material removal processes, "subtractive-manufacturing" would no longer be the only material-working process used in manufacturing. A tool or head moving through a 3D work-envelope transforming a mass of raw material into a desired shape layer by layer i.e. 3D printing also known as "additive manufacturing", was heralded as the breakthrough in next generation manufacturing.

At the same time, starting in the late nineties the sector began to see diversification into two focus areas. First was the high-end, where 3D printing, although still quite expensive, focused on high value, highly engineered, complex parts. This area has experienced tremendous growth in recent years, especially with the advent of metal 3D printing. Years of R&D investments have started to pay off with successful production applications in aerospace, automotive and the dental industry.

[1] https://3dprintingindustry.com/3d-printing-basics-free-beginners-guide/history/

Second was the lower end of the spectrum, which focused on manufacturing 3D printers that were used for improving concept development and functional prototyping, as office and user friendly cost-effective systems. This was the prelude to the desktop 3D plastic printing systems, which today can be purchased for as little as $400 and are widely used by hobbyists to produce trinkets and toys in schools; university labs as well as for some industrial applications.

According to a 2016 PWC survey of 900 companies from 12 countries, "24% of all companies perceive 3DP as a strategic or important topic" for the future of their companies[2]. According to the same report,"2% or more of the total revenue of companies with 3DP experience is already generated by 3DP products." Gartner interprets a technology as "mainstream" once the adoption level reaches 20%.

Despite the slow general uptake, our research identified at least two industries that have commercialized 3DP as a mainstream technology with almost complete adoption in many advanced economies. The first industry is dentistry, where 3DP is now used to produce dental crowns, bridges and other advanced dental implants. The second example is the hearing aid industry.

Dentists now regularly use digital scans to manufacturer 3DP implants for their patients. The ability of dentists to directly manage this customization is a major enabler for adoption in the field, and has disintermediated traditional metal implant manufacturers. Interactive design control has empowered dentists and led to improvements in customer satisfaction.

Customized hearing-aid shells and ear molds are also now being commercially produced using 3DP. It is estimated that 60 million 3D printed hearing aids are in use already. According to an article in the May 2015 issue of the Harvard Business Review "U.S. hearing aid companies converted to 100% 3-D printing in less than 500 days".

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[2] How will 3D printing make your company the strongest link in the value chain? EY's Global 3D printing Report 2016

Although overall adoption of 3DP is still in its infancy, in markets within which the value proposition is strong, the technology has seen rapid adoption. The key question we asked is, why has it taken so long for 3D printing to mature? Our objective was to identify applications and industries that have characteristics that make them most likely to lead the way in adopting this technology. Using the lessons learnt from dentistry and hearing aids and other industry use cases, we identify the conditions that are conducive to making additive manufacturing mainstream.

Methodology

In his lecture on "Iterating to Insights: Mining Thought Experiments for Strategic Insights", Professor Duncan Simester, NTU Chair in Management Science at MIT Sloan, who mentored and advised us on our thesis work, explains that "understanding how to use the framework to engage in strategic thinking is relatively rare". He further explains that "to engage in strategic thinking managers need to know how to think strategically, and they need time to think. Both ingredients are in short supply."

We used the iterating to insights approach for our thesis work. The approach relies on the "power of thought experiments". The idea is to start with a set of known facts and then think deeply to develop a theory capable of explaining the facts. We began by postulating a specific use case for 3D printing, and analyzed it around the following criteria:

a) Who is the Customer?

We focused our use cases on two scenarios; whether mass adoption of 3D printing will be driven by sales to consumers (for printing at home) or by sales to industrial manufacturers. We then described a potential single customer for each use case in vivid detail and brainstormed how 3D printing could create value for them. Could it result in reduced cost by improving operational efficiency or could it improve the customer experience to create more demand?

b) Adding a Competitor and a Product or Service Solution to the Use Case

For each customer, having identified a single decision criteria, we then described a service solution, selected a competitor and identified the sources of differentiation. For example, we could start out by describing our user as Thomas, a happily married father of two, who makes

$250,000/year and lives in Boston. He lives in an old Georgian house and is a do-it-yourself-fanatic, whose current project is to repair his ceiling moldings. A 3D printing service solution for Thomas could be to have a 3D printer at home, which he uses to print the moldings. A potential competitor could be to simply buy prefabricated molding from a hardware store such as Home Depot. His preferred option depends on the cost of the printer, its ease of use and how often Thomas will use it. For example, if it is very expensive to purchase and difficult to use then Thomas will most likely opt to buy prefabricated molding from a hardware store.

c) Add a Partner

In the final step, we identified a potential partner in the value chain. For example in Thomas's example, 3D companies could sell 3D printers to hardware stores, so that these could then make custom 3D prints for customers such as Thomas.

We then iterated the use cases by changing one feature at a time. This could include the customer, competitor, product, or partner. In Thomas's case, we could change the competitor from Home Depot to an e-commerce platform such as Amazon and discuss how the value proposition for Thomas would change if Amazon started offering printing services for ceiling molding. We repeated this exercise several times before moving onto a new use case.

The aim of the thinking exercise was to identify strategic insights that are surprising yet compelling. Our goal was to find five to six insights that an investor in a 3D printing company or a startup could use to decide whether an application or market is worth pursuing or not.

In terms of planning and scheduling, we broke the work into two separate but complementary steps. Firstly, we used the IAP period in Jan 2017 (4-weeks) to iterate and generate ideas by brainstorming in a team of four. Mr. Jasjit Makol and Ms. Malene Kvist Kristensen (classmates in the 2017 Sloan Fellows program) contributed immensely to the search for insights. At the end of this period, for discussion and vetting of the ideas, we finalized the insights using feedback from other 2017 Sloan Fellows.

In the second phase we distilled the ideas into a coherent list of insights. This step included a significant amount of research, including discussions with industry experts. The resulting insights are summarized in the list below. They suggest that adoption of 3D printing in manufacturing will happen in industries when a combination of these conditions are met:

1. Products derive value proposition through customization
2. There are underserved urgent customer needs because the supply-chain is inefficient.
3. Additive manufacturing facilitates increases or decreases in industry clock-speeds.
4. There is end-to-end participation in the supply-chain by one or more large manufacturers.
5. 3D Printing enables manufacturing of products that could not otherwise be made.

Current State of Play

3D printing is a growing industrial sector that is redefining what a manufacturing job may look like in future. Growing political will and pressure to develop manufacturing jobs nationally, coupled with 3D printing's ability to redefine conventional blue collar jobs into a creative, hi-tech endeavor may attract the millennial workforce back into the manufacturing industry.

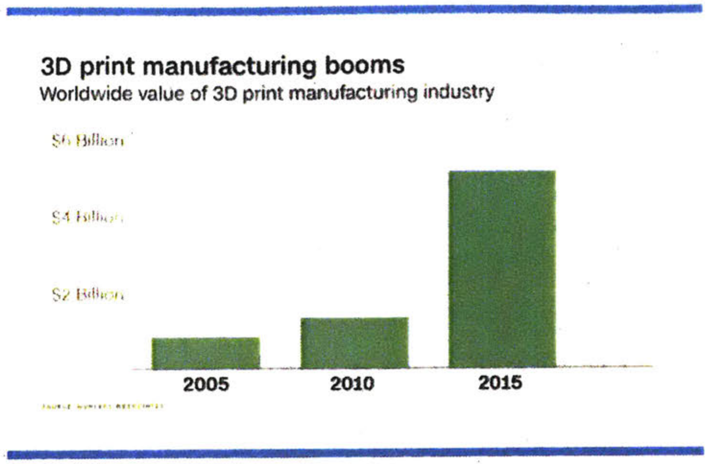
The company Voodoo Manufacturing provides one such example. Voodoo is a 3D printing company based in Brooklyn, New York.[3] With 160 computerized printers humming in the background, it feels more like a high tech start up than a traditional blue-collar firm.

Picture 1: Jim Allen, left, and Andrew Rosa at Voodoo Manufacturing in Brooklyn, N.Y., a 3D print manufacturing company.

As shown in diagram 1 below, the 3DP manufacturing industry was valued at $5.1 billion worldwide in 2015, up from less than $1 billion a decade ago.

[3] http://money.cnn.com/2017/03/27/news/economy/american-manufacturing-jobs/index.html

Diagram 1: Worldwide Value of 3D Printing



A distinguishing feature of 3DP from conventional manufacturing, is the economic feasibility of distributed manufacturing. 3DP as opposed to centralized manufacturing can deliver value by producing products when needed and at the location of demand. This plays into a current accelerating trend, where customers are demanding increased customization of products. 3DP could enable manufacturers to address this trend. There are obvious current constraints of speed, technology and raw material cost and availability. However, 3D printing must be evaluated on a medium to long term perspective when technological improvements may mitigate many of these constraints.

Insight 1: Products Derive Value Proposition through Customization

Given a choice, most consumers prefer individualized; custom products, instead of mass-produced, "one-size-fits-all" products. However, high CAPEX outlay required in setting up manufacturing facilities coupled with high costs for tooling, product-molds, set-up and change-over costs make it prohibitive to produce affordable custom goods with traditional manufacturing techniques. This is because conventional manufacturing relies on "economies of scale", where cost per unit of output decreases with increasing scale as fixed costs are spread out over more units of output[4]. For instance, when a person with a shoe-size of 9.32 has to buy a shoe, he/she has to choose either a size 9 or a size 10. Current mass production set-ups cannot make size 9.32 as cost efficiently as the regular sizes

Additive manufacturing addresses this cost problem to a significant extent. In 3D printing the marginal cost of design and customization is very low. The manufacturing cost is almost independent of customization. Design parameters in a digital file can be altered at negligible cost to address any shoe size. In addition, the actual manufacturing cost for 3DP is almost agnostic to design changes or number of SKUs. As a result, 3DP enables economic production of customized low volume products including highly complex products with intricate designs. Such products are very difficult, and in most cases, too expensive to manufacture economically through traditional subtractive means. These two factors make 3D printing an ideal process for production of custom products. To substantiate the above argument, we will use the following two examples that are chosen from two very different industries.

a. Mass produced vs. custom built footwear: In the following table, we compare the manufacturing steps involved in making the "outsoles-of-shoes" for the two process types - 3DP vs. conventional manufacturing - to make the case for using 3DP to manufacture custom made shoes.

[4] https://en.wikipedia.org/wiki/Economies_of_scale

Table 1: Simplified Process for Shoe Production

Conventional Process	3DP Process
Digital file of measurement.	Digital file of measurement.
Custom mold from digital file.	Printing the outsole.
Injection molding of outsole.	
Post Processing.	

Scanning and digitization of feet has become a quick and inexpensive process. Furthermore, for an adult, this needs to be done only once, as the stored file can be used multiple times if new shoes are to be made by 3DP. Meanwhile, producing a custom mold for individual customers using the conventional process is extremely costly. Hence, to capture "economies of scale", shoe manufacturers segment shoe sizes into relatively large categories of standard size categories that can capture fairly large numbers of people. This allows a limited number of molds to be produced. Each mold can then be used to produce tens of thousands of shoes, spreading out the investment costs.

3DP on the other hand allows shoe sizes to be segmented into much smaller groups. This "mass- customization" is possible as there are no standard molds and no expensive set-up and retooling costs. In other words, the marginal cost to produce different SKUs is negligible. 3DP thus opens up the opportunity to add custom features such as individualized insoles of shoes at affordable cost.

b. <u>Prosthetics</u>: Another good example of the use of 3D printing for customization is prosthetics. Prosthetics require one of the most complex customization processes, due to variability of requirements of individual patients. No two individuals are identical when replacing a lost body part. The need for good and well customized prosthetics is critical for the patient's future quality of life. Unfortunately there is growing demand for prosthetics for many reasons such as land mines, road or other accidents, and congenital conditions.

The development and customization of prosthetics is an iterative process which works best when the patient is physically available for fitting tests and optimization, so that the artificial limb can be adjusted for best fit through successive iterations. 3DP is replacing the conventional prosthetics production due to some key advantages. First, it can rapidly customize and produce progressive versions of improved artificial body parts at relatively low cost. A good example is the company Cyborg Beast, which specializes in this field.[5] Cyborg Beast can make a prosthetic hand for as little as $50, whereas a conventional prosthetic hand may cost $30,000 to $40,000.

A second major advantage is the ability of 3DP technology to simplify a relatively complex traditional method of Prosthetics development. Patients had to make repeated visits to clinics and wear heavy development molds before they finally got an expensive prosthetic, which required repeat adjustments. Digital design combined with 3DP eliminate the need for molds and tooling, thus offering a significant advantage in the form of well customized prosthetics.

Lastly, as Prosthetics development through 3DP matures, it will be possible to manufacture artificial limbs closer to the geographic location of the patients (please refer the earlier discussion of distributed manufacturing in the section on "current state of play").[6]

Our observations and research on the industry indicates that there are two main limitations to consider when deciding to use 3D printing for commercial scale customization in a manufacturing set-up:

[5] The Atlantic Daily Feb 22, 2017

[6] Distributed manufacturing also known as distributed production, cloud producing and local manufacturing is a form of decentralized manufacturing practiced by enterprises using a network of geographically dispersed manufacturing facilities that are coordinated using information technology. It can also refer to local manufacture via the historic cottage industry model, or manufacturing that takes place in the homes of consumers. *(Source: https://en.wikipedia.org/wiki/Distributed_manufacturing)*

- **Careful consideration of timing:** 3D Printers, especially metal printers, are still expensive to purchase and their printing speeds are still relatively slow. Careful product selection is required for 3DP to be economically feasible. For example, a professional metal 3D printer from EOS or STRATASYS costs $100,000 to $500,000[7] and requires over 7 hours to print a relatively simple stand for tablets (14cm long, 4.2cm high and 9.8cm wide)[8].

  For this reason, 3DP is currently most suitable for small form factor (less printing time), and high value products with relatively complex designs. Perfect examples include dental crowns and bridges as well as hearing aids, all of which have already fully adopted 3DP. However, the long-term cost trends for 3DP look encouraging. As the technology improves, both equipment and raw-material-feed costs are predicted to continually decrease while printing speed accelerates. This will enable use of 3DP for an increasing number of products.

- **Which process steps in the value chain will use 3DP**: Another limitation arises when a product cannot be entirely produced by 3DP. In such cases, it is important to strategically determine where along the supply chain it makes the most sense to utilize 3D printing. In the case of custom shoes, it might be better to use 3D printing for custom insoles rather than outsoles. Outsoles will require the rest of the shoe to be adapted, which is costly and impractical. Custom insoles however, can simply be used with standard shoes. Although it may appear as if 3D printing is ideal only for products that can be fully 3D printed, customization that can be added towards the end of the production chain could also be an obvious fit.

[7] https://all3dp.com/metal-3d-printer-guide/
[8] http://www.thingiverse.com/thing:605818

Insight 2: There Are Underserved Urgent Customer Needs Because the Supply-Chain Is Inefficient

The insight in this section deals with markets of "urgent" needs which are currently underserved due to variable and infrequent demand. These markets are underserved because current supply networks are based on centralized manufacturing and economies of scale. These "urgent" needs are thus underserved due to frictions of cost, timing and logistics within these networks.

We present a few use-cases from industries that find it difficult to get the product or service required for smooth operations. We also present examples of how these industries could use 3DP to service these needs in the not so distant future. One characteristic of all use-cases in this section is that users are locked-in with a product or service where the technology has become obsolete due to disruption in the sector. However, these users continue to use the product/service for various reasons although they have no supplier contracts to service their break-down or maintenance needs.

Out of many real-life examples, we chose two present day use cases that face this issue. We also present the energy generation market as an example of an industry, where we anticipate a huge potential opportunity for 3DP to service "urgent needs", in the not so distant future. The present day examples are as follows:

a) New York MTA[9] - New York's mass transit subway system manufactures its own spare-parts and components as many of its original suppliers are now non-existent.

b) Vintage car owners do not get spare parts as companies no longer produce these parts or in some cases the companies no longer exist.

The New York MTA is one of the world's biggest, most complex and heavily used subway systems. The modular growth of the rail-network in the early 1930's led to multiple technologies and vendors, most of which no longer exist.

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[9] The Atlantic Nov 13, 2015, New York Subway case study.

As a result, the NY MTA cannot find or buy replacement parts from manufacturers; it therefore refurbishes them in its own engineering workshops using conventional technology. Manufacturing of the more complicated parts could be done with 3D printing as the design and use of these parts is fully controlled by the MTA. As noted in the next section, end-to-end control of the supply chain, is a significant enabler for adoption of 3D printing.

Vintage car spare-parts are another good use-case. Due to infrequent demand and limited markets, manufacturers with conventional supply networks are unable to supply parts. The car owners have to depend on alternate work-arounds that are costly and offer poor quality. 3D printing can be an excellent business model as spare designs, sourced from original manufacturers or other authenticated sources, can be held as virtual inventory. Manufacturing can then be done based on customer demand.

In the future these issues may not be restricted to a niche market or industry. We identified energy generation as one example of a large industry that could be a candidate for alternate supply-chains for service fulfillment. Utility companies using fossil-fuel generation, are being disrupted by wind & solar generation.[10] More generally, as shown in diagram 2 below, the energy industry is going through a significant revolution with renewable energy sources gaining significant market share. The amount of energy generated through non-hydro (wind and solar) renewable sources is now comparable to the amount generated through nuclear power.

The marginal cost of non-hydro energy is almost zero, this aspect makes it highly attractive for adoption. However, there is one major issue associated with this technology, which is referred to as "intermittency" i.e. sunlight and wind power are not uniformly available at all times for electricity generation. Since energy storage is a major technological and commercial issue, adoption of renewables requires maintenance of current fossil-fuel based energy generation plants to make up for intermittency.[11] It is therefore possible that maintenance of legacy energy generation systems could become a fertile market for 3DP if traditional equipment manufacturers start to exit this industry.

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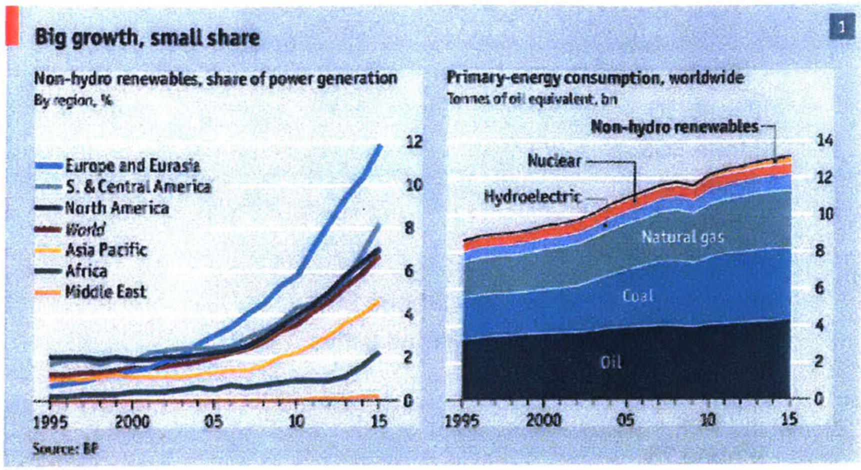
[10] The Economist – 25th Feb. Clean energy's dirty secret.
[11] Economist March 2017

Diagram 2: Non-Hydro Renewables Share of Power Generation



Insight 3: Additive Manufacturing Facilitates Increases or Decreases in Industry Clock-Speeds

In his book "Clock Speed: Winning Industry Control in the Age of Temporary Advantage[12]" Charles Fine popularized the concept of clock speed. The basic concept of clock speed is that various industries have a differing pace of innovation and hence the rate of major changes and concomitant product lifecycles within industries is determined by their respective clock speed.

The airline, automotive and pharmaceutical industries are slower clock speed industries. An aircraft model can have a lifetime of up to 20 years, for example Boeing announced that it would stop taking new orders for the Boeing 747-400 passenger aircraft in March 2007, 18 years after it first entered service in February 1989.[13] This is very long compared to high clock speed industries such as computers or mobile phones.

As shown in the table below, Apple released the first iPhone in 2007 and they have introduced a new model, with greatly enhanced features compared to the previous one, every single year since then.[14] The clock speed of the mobile phone industry is therefore much faster than that of the aircraft industry.

[12] Clock Speed Author Chris H Fine
[13] https://en.wikipedia.org/wiki/Boeing_747#747-400
[14] http://www.t3.com/features/a-brief-history-of-the-iphone

Table 2: IPhone Models 2007 - 2017

Year	Phone Model (s)	
2007	iPhone	
2008	iPhone 3G	
2009	IPhone 3GS	
2010	IPhone 4	
2011	IPhone 4S	
2012	IPhone 5	
2013	IPhone 5S	IPhone 5C
2014	IPhone 6	IPhone 6 Plus
2015	IPhone 6S	
2016	IPhone 7	
2017	IPhone 7S	

We argue that industry clock speeds are greatly influenced by the capital requirements associated with new product development. The Dreamliner project is reported to have cost Boeing $ 32 Billion[15], while the Airbus A380 cost $ 28 Billion to develop.[16] These high investment costs for product development lead to longer amortization periods, which is a key contributing factor for the slow clock speed in aircraft manufacturing. Similar logic applies to the automobile and pharmaceutical industries.

We found it surprising that adoption of 3D printing has been faster in industries with slower clock speeds. We present two arguments as to why this may be the case. The first argument is related to the economic efficiency associated with 3D printing. Eliminating the need for retooling factories can significantly reduce capital requirements for new product development and increase clock speeds. We will explain this first point in depth before presenting the second argument.

Product changes in traditional manufacturing can be economically inefficient due to high capital; tooling and change-over time requirements. For example, automobile production plants need to be sometimes closed for months leading to lost sales and underutilized workforce. When Ford

[15] http://www.seattletimes.com/business/boeing-celebrates-787-delivery-as-programs-costs-top-32-billion/
[16] https://www.bloomberg.com/news/articles/2016-07-12/airbus-plans-to-cut-annual-a380-deliveries-to-12-as-of-2018

introduced the F-150 truck from 2014 to 2015), they invested $359 Million to retool their Dearborn Michigan plant, which had to be closed for 13 weeks. The F-150 truck is America's top selling truck with sales averaging 60,000 units per month.[17] Closing the Dearborn plant for 13 weeks greatly impacted Ford's bottom line. In the future advanced metal 3D printing may mitigate some of these issues as retooling can be minimized. This will greatly reduce CAPEX, change-over-time and worker retraining requirements, which will help to accelerate clock speed.

Our second argument is that 3DP can also result in the opposite effect; decreasing clock-speeds by making it easier to create customized variations around the core technology. This can enhance the lifespan of the core technology itself. The Boeing 747-400 provides a good example. Before introducing the 747-8 in March 2011, Boeing built different versions of the 747-400 to address different market requirements. These included the 400 passenger transport with higher seating, 400F freighter without upper deck, 400D domestic (624 seater) and others like 400M, 400ER and 400ERF. The new 747-8 is designed to be "quieter, more economical and environment friendly"[18] than the 400. It is possible that if the use of 3DP had been more advanced in aircraft manufacturing at the time, these goals could have been achieved using the 400 platform.

Fast forward to 2017 where GE's LEAP engine that contains nineteen 3D printed fuel nozzles, which are five times more durable than the previous nozzles are expected to go into production. 3DP allowed "the design team to reduce the engine's weight by hundreds of pounds compared to the same size engine built by using metal parts, increase the internal temperature and make it more efficient"[19] The LEAP engine is expected to have 50% lower NOx emissions than current regulatory limits, double digit improvements in noise and emissions, 15% fuel efficiency improvements at same CO_2 emissions. Cumulative estimated savings are expected to be up to $1.6 million /airline/year in fuel costs.

[17] http://www.procurementbulletin.com/fords-new-aluminum-f-150-requires-retooling-of-major-manufacturing-facilities/
[18] https://en.wikipedia.org/wiki/Boeing_747
[19] http://www.gereports.com/post/80701924024/fit-to-print/

This simple example illustrates how 3DP could reduce industry clock speeds by enabling modifications to products which obviate the need for more radical changes to the core product technology.

To summarize; our research shows that 3DP could either increase or decrease industry clock speed. On one hand, using the automotive industry as an example, we showed that 3DP could obviate the need for retooling during model changes. This greatly reduces CAPEX and retooling-downtime, thus reducing amortization periods and enabling faster product cycles and accelerating industry clock-speed. On the other hand, using the airline example, we showed that 3DP could increase industry clock-speed by making it easier to create customized variations around the core technology. This enables greatly enhanced performance with limited changes to the core technology itself, thus leading to longer clock-speeds for the core technology.

Insight 4: There Is End-to-End Participation In the Supply-Chain By One Or More Large Manufacturers.

Many large manufacturing corporations, which produce high-value products control their entire supply-chain by end-to-end participation (E2E). By E2E we mean that they are fully integrated across all steps in the supply chain including procurement, manufacturing and assembly. This E2E control is necessary to enable these corporations to exercise full ownership of technology, quality and consistency of their products. Examples of such high value products include:

- Jet engines from manufacturers like GE and Rolls Royce.
- Internal combustion engines for automobiles.

E2E participation is crucial in fostering early adoption of new technologies. Our research shows that jet engine and automobile manufacturers are selectively adopting 3DP for their complex parts. Our analysis reveals three main reasons for this:

1. **Performance and quality standards of the end product owned by the corporation:** An E2E capability can contribute to the adoption of a new technology by increasing the incentives to invest in new technology. As we discussed earlier, GE now manufactures

aircraft engine nozzles using a 3DP process. GE's E2E capability has been critical for design, development, testing and quality control of this key component in jet engines. GE owns every production step from material-sourcing, manufacturing and post processing. A fully integrated company like GE, will develop the skills and capabilities required to pioneer design, engineering, printing and qualification of the component.

2. **End to end view of technological capabilities and limitations:** A corporation with E2E supply chain participation, by definition has a comprehensive view all manufacturing processes and will take a holistic view of adoption of a breakthrough technology. These corporations may start with one or more components of their product assembly, but they usually take a longer term view to the adoption of the technology. This is usually done by detecting gaps or bottlenecks in the supply chain and plugging them with new technology opportunities. For example, GE Additive, the 3DP division within GE, provides engineering consulting and financial services.

   We previously described the LEAP jet engine, which features 3-D printed fuel nozzles, carbon fiber fan blades and ceramic matrix composites. This is a highly complex product that will be supplied to an in-house customer (GE Aviation). All the process technologies required to build this part are internal to GE, including software and design all the way through to verification, SPC and final product testing and qualification.

3. **Ability to capture value along the whole supply chain:** A fully integrated firm involved in making value added hi-tech products has stronger incentives to create an eco-system to develop technology to improve its supply-chain capabilities. For example, GE is motivated to make the necessary investments to develop 3DP capabilities because it can capture value created anywhere along the value chain.

   GE has created a new business division with an investment of over one billion dollars, dedicated to 3D printing, GE Additive. GE Additive is investing in an eco-system for developing 3DP as the future of GE's manufacturing strategy.[20] GE Additive offers multiple value added services including:

- Machines for powder bed metal printing (using e^- Beam & Laser fusion)
- Raw materials (e.g. metal powders)
- Engineering consulting services and access to GE Global Network.
- Education ($10 million in primary and collegiate education)
- Financing (GE Finance)
- Software (GEs Predix Platform)

In contrast, a narrowly focused firm that is exclusively focused on supplying 3D printers, cannot capture value created in the downstream processes, such as final product qualification. Even if they realize a need to develop better tools for product verification and SPC post printing, it will not make business sense to invest in doing so. At least some of the value they create risks being captured by firms elsewhere in the value chain.

E2E supply chain participation is not an absolute requirement for mass adoption of 3D printing. However, our assessment is that fully integrated companies will play a leading role in enabling the mass adoption of 3DP for applications, particularly in the following settings:

- Complex products, where 3DP simplifies manufacturing, which are used in critical environments. Examples include aircraft engine parts, automotive breaking systems, and medical devices. The safety factor becomes even more critical where parts require regular maintenance during their lifecycle for example aircraft maintenance.
- When the functionality and quality of such complex products is strongly influenced by interdependencies between several steps along the supply chain. These settings often require E2E control of the supply-chain by integrated manufacturers.

[20] http://www.geadditive.com/#offerings

- Applications where the products require high CAPEX and complicated post processing steps such as highly accurate annealing or long qualification processes such as FDA approval are mandatory.
- 3D printed parts that have different material properties than those produced using traditional manufacturing methods. New product specifications and qualification methods will have to be developed for such 3D printed parts. These applications require close cooperation between end users, manufacturers and suppliers. For example, in the case of GE's LEAP nozzle, GE Aviation worked closely with different groups within GE-Additive to qualify new parts. This close cooperation becomes more difficult across firm boundaries (IPR, Culture etc.) and therefore constitutes a barrier to adoption of new technologies in the absence of vertically integrated players.

Insight 5: 3D Printing Enables Manufacturing of Products That Could Not Otherwise Be Made

There are certain applications for which 3D printing enables manufacturing of parts that would otherwise be too expensive or even impossible to manufacture. A good example is 3D bio printing of human organs. Two early pioneers in the field are Organovo and RenovaCare. Organovo offers "bio printed human tissue models…. created using a proprietary 3D bio-printing process. The tissues remain viable and dynamic for an extended time in vitro and exhibit functional features similar to natural tissue environment."[21]

RenovaCare uses 3D bio-printing to offer "spray-on cells for rapid healing" that uses patient's own stem cells, which are sprayed onto wounds using a novel SkinGun™ device."[22] Apart from medical applications, personal product companies like Unilever; P&G and L'Oréal use artificial skin-substrates to lab test their products for efficacy. This technology presents a significant opportunity to produce more realistic skin-substrates for development of safe products.

Bio-printing is already making an impact on new treatment methods. Using cells extracted from human beings or other living organisms, scientists can use 3DP to grow replica organs or muscles within weeks. This may allow more customized therapies, such as that offered by RenovaCare, to develop replacement organs using a patient's own tissue, mitigating rejection risk by the immune system.

In his TEDxEstVan talk titled "3D printing is medicines next frontier", in which he imagines life in the year 2050; Sam Wadsworth, co-founder and chief scientific officer at the Canadian 3D bio-printing company Aspect Biosystems outlines some of the possibilities that bio-printing will enable in future.

Aspect Biosystems has demonstrated use of tissue extracted from the airway muscle of an asthma patient to 3D print replica airway muscles, which react in the same manner to stimuli as in the patient. These replica muscles also react to Ventolin, a drug used in the inhalers of asthma

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[21] http://organovo.com/
[22] Copyright © 2015 RenovaCare, Inc. Read more at: http://renovacareinc.com/technology/

patients, in the same way as an asthma patient would. Another example is "Organovo ExVive™ 3D Bio printed liver models that are available through Organovo's preclinical in-vitro testing services, which provide predictive liver tissue-specific toxicity marker assessment as a supplement to in-vitro and preclinical animal testing."

Such bio-printed products could dramatically improve the efficacy and efficiency of current drug development procedures by increasing the success rate of pre-clinical models. The FDA process for drug development requires new therapies to be first tested in preclinical models before they can proceed to clinical trials. Preclinical trials typically involve testing the new drug on tissue cultures and animals. 90% of drugs fail when crossing the chasm from animal testing to clinical trials. 3D bio printing will enable preclinical trials on manufactured human tissue, potentially greatly improving the success rate and speed of new drug development.

Another interesting area for bio-printing is manufacturing of meat. According to an FAO report titled "how to feed the world in 2050"[23], the world's population is estimated to reach 9.1 billion people by the year 2050. In order to keep up, annual meat production will need to rise by over 200 million tons to reach 470 million tons per year. This will require a massive increase in the number of animals raised for consumption, requiring vast expanses of land and impacting climate change as the amount of methane in the atmosphere due to farm animals increases dramatically.

Lab-grown, "cultured" meat could become an alternative source of protein. Cultured meat is "a method where stem cells from skeletal muscle of cows are cultured in vitro to gain edible muscle tissue."[24] Some scientists believe that bio-printing of meat could be used to replace or supplement meat from living animals for human consumption. However, this scenario is still far from reality as cultured beef is currently too expensive to be commercially viable. Professor Mark Post of Maastricht University, created the first lab-grown burger that was eaten in London in 2013.[25] At a cost of $330,000 it still remains more a lab experiment than a mass consumption product. Leather and other animal-based products could also be bio-printed in the future.

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[23] http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf
[24] http://dx.doi.org/10.1016/S2095-3119(14)60889-3
[25] http://www.bbc.com/news/science-environment-23576143

Summary of Insights

Using the iterating to insights approach we came up with 5 insights vis-a-vis the challenges and opportunities for mass adoption of 3D printing. The insights are summarized in the following table:

Table 3: Summary of Insights

Insights	Examples	Explanation
Products derive value proposition through customization	Custom shoes and prosthetics	Variable cost of 3DP is agnostic to design changes required for customization. This allows customization at low cost by 3DP.
There are underserved urgent customer needs because the supply-chain is inefficient	New York MTA and vintage car parts	3DP can service "long tail" products at minimal cost as no physical inventory is required. A digital design can be produced on demand and the variable cost is independent of quantity.
Additive manufacturing facilitates increases or decreases in industry clock-speeds	Automotive and aerospace industries	3DP can shorten amortization periods by reducing CAPEX and amortization time, thus accelerating innovation or clock-speed. Conversely, it can decrease clock-speed by prolonging use of a core technology by enabling custom enhancements around it.
There is end-to-end participation in the supply-chain by one or more large manufacturers	Aircraft engine production (LEAP from GE).	Large, vertically integrated manufacturing firms can capture value anywhere along the supply chain These firms therefore drive adoption of 3DP as this incentivizes them to invest in plugging technology gaps and lead the development and expansion of 3DP.
3D Printing enables manufacturing of products that could not otherwise be made	Bio-printing human parts	3DP enables completely new innovative applications, where the burden of conventional manufacturing is not a barrier.

The following is a brief description of each insight in more detail:

a) Products derive value proposition through customization

If such products are available at reasonable cost; most customers prefer custom, individualized products to non-custom mass products. Conventional manufacturing, which requires high capex and economies of scale, cannot deliver customization at a reasonable cost. However, 3DP can deliver customized solutions with little incremental cost. Therefore, markets in which customers are willing to pay a premium for customization offer fertile opportunities for 3DP solutions.

b) There are underserved, urgent customer needs because the supply-chain is inefficient

3D printing makes manufacturing of "long tail products", which would be uneconomic to produce and distribute using traditional supply chains, economically viable. For example, owners of vintage cars often have difficulty to repair their priced possessions. This is because car manufacturers have no incentive to produce and hold spare parts for vintage car models since this is not a profitable business for them. The quantities do not support a viable mass production model. Vintage car dealers could use 3DP to produce their own parts by creating digitized plans of obsolete parts and printing them as required for repairs.

c) Additive manufacturing facilitates increases or decreases in industry clock-speeds

3D Printing could either increase or decrease industry clock speed. In the automotive industry for example, 3DP obviates the need for retooling during model changes. This greatly reduces CAPEX and retooling-downtime; thus reducing amortization periods and enabling faster product cycles. This results in faster industry clock-speed.

On the other hand, 3DP could increase industry clock-speed. For example in the airline industry, 3DP makes it easier to improve performance by creating better performing jet engines. This can greatly enhance performance such as fuel consumption and environmental pollution without changes to the core design of the airplane itself. This leads to a longer lifetime of the core technology of airplane design, which reduces industry clock-speed.

d) There is end-to-end participation in the supply-chain by one or more large manufacturers

Many large firms with products that are required to operate in critical environments control their entire supply chain through end-to-end participation (E2E). E2E participation allows these firms to capture value across the whole supply chain. This incentivizes vertically integrated companies to deploy emerging technology not only on the basis of current merits but also to develop future roadmaps for their industries. A good example is GE Additive, which offers additional services such as funding education initiates and customer financing for equipment purchases. This helps to accelerate adoption of 3DP.

e) 3D Printing enables manufacturing of products that could not otherwise be made

3D printing enables totally new, innovative products to be manufactured. For example 3D bio-printing of human organs is being used by companies such as Organovo to produce bio-printed human tissue such as human livers for clinical trials. These could eventually be used as replacement organs for sick patients.