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An Economic and Technological Analysis of 3D Printing in the Automotive, Aerospace, and Medical Industries

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AN ECONOMIC AND TECHNOLOGICAL ANALYSIS OF 3D PRINTING IN THE AUTOMOTIVE, AEROSPACE, AND MEDICAL INDUSTRIES

by
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A thesis submitted to the faculty of the University of Mississippi in partial fulfillment of the requirements of the Sally McDonnell Barksdale Honors College.

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ABSTRACT

Although 3D Printing currently produces only a few parts in the automotive, aerospace, and medical industries, imminent economic changes and technological advances will lead to mass adoption of the technology within the next decade. In the past ten years, 3D Printing technology has advanced so rapidly that the previously unknown manufacturing technique has become a billion dollar industry. Today, 3D Printing pervades many industries. This thesis focuses on the use of 3D Printing in the automotive, aerospace, and medical industries. After an introduction examining 3D Printing and general economic production theory, this thesis identifies current and potential uses for 3D Printing and conducts a cost analysis for each of these three industries. Based on the evidence from these analyses and widely forseen imminent economic changes, 3D Printing will continue to advance over the next decade, becoming an integral manufacturing technique.
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To understand a thesis about 3D Printing, it is crucial to understand what 3D Printing is, how it works, what it can do, and why it is better at some tasks than other manufacturing methods. In this section, I will provide general background for 3D Printing, including what it is, when it was invented, how it works, and differences between various 3D Printers. I will conclude the section with an explanation of why analyzing the automotive, aerospace, and medical industries can effectively analyze 3D Printing as a manufacturing technique.
What is 3D Printing?

3D Printing refers to a manufacturing technique where machines, called 3D Printers, build products by adding one layer at a time. The first 3D printers were patented in the early 1980’s. Charles Hull, referred to as the “Father of 3D Printing,” cofounded 3D Systems Corporation shortly after filing a patent for a stereolithography apparatus (SLA) in 1986¹.

There are many variations of 3D Printing techniques, such as selective laser sintering, fused deposition modeling, direct metal laser sintering, ballistic particle manufacturing, and laminated object manufacturing. 3D Printing is also referred to as “additive manufacturing” because the 3D printing process adds material to a product rather than machining material away².

3D Printing, regardless of the type of printer or material used, consists of the same basic steps³. First, a designer creates a three-dimensional blueprint using computer-aided design (commonly called “CAD”). Next, the designer loads the printer with raw materials and prepares the printing stage for use. 3D Printers usually use complex plastic polymers, but some produce parts using metals or binding solutions. Some printers require adhesives or cleaning before use to assist the manufacturing process. After the 3D Printer is prepared, the designer sends the CAD design to the printer. The printer then begins to process and create the product. Most printers use a manufacturing process called

extrusion, where the raw material is melted and pushed through a nozzle on the printer. The nozzle deposits material into a thin cross-section based on the CAD drawing. The extrusion can take anywhere from a few seconds to many weeks, based on the complexity of the design. After the product is complete, the creator performs some post-processing, which can be as simple as prying the printed product off of the print deck or as complex as removing support structures and sanding the object.

**Major 3D Printing Methods**

There are seven types of 3D Printing that are most widespread, including material extrusion, material jetting, binder jetting, power bed fusion, directed energy deposition, sheet lamination, and vat photopolymerization. Each of these printing methods has distinct advantages and disadvantages.

In *material extrusion*, the printing material is melted and extruded through a print nozzle. The printer calculates cross-sections based on a CAD drawing and deposits the polymer into the calculated areas. The polymer solidifies, bonding to lower layers. The nozzle then rises and repeats the process. This technique varies widely in the amount of time it takes to complete, based on the complexity and thickness of the object⁴.

In *material jetting*, a printer deposits raw material through an inkjet printer head. This technique usually uses a photopolymer (a plastic that requires light to harden), but can also use waxes or similar materials. This technique can produce precise parts or use

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multiple materials through the use of additional printer nozzles, but material jetting suffers from relatively expensive machines and slow build times\(^5\).

In *binder jetting*, a thin layer of powder is rolled across the printer stage. The printer then sprays a glue-like substance called a binder to fuse the powder together in specific areas based on cross-sections calculated from the CAD file. The process repeats until the printing ends. The excess powder is then removed and saved for later. This process can be used to create large parts, but suffers from relatively expensive materials and relatively fragile products. *Powder bed fusion* uses the same process as binder jetting but with one added step. In this printing technique, the layers are fused together using a heat source, either by melting (with heat) or sintering (with pressure). This process produces high quality, strong metal or plastic polymer parts, but suffers from expensive and limited raw material choices\(^6\).

In *directed energy deposition*, a high-energy source, such as a laser, melts wire or powder metal into layers. This method is typically used to either build large parts or to repair broken parts. Directed energy deposition usually requires significant post processing\(^7\).

In *sheet lamination printing*, layers of material are bonded together with adhesives. Sheet lamination allows manufacturers to use low-heat when creating products, which means heat-sensitive materials, such as electronics and paper, can be

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used without being destroyed. This process costs the least of any additive manufacturing process, but is less accurate and creates weak bonds between layers.\(^8\)

In *vat photopolymerization*, a liquid resin is cured in layers using special lights. Bright lights, such as a laser or a projector, are used to trigger a chemical reaction, hardening the polymers. Although the machines are expensive and the material choices are limited, the technique can produce parts within narrow tolerances and with fine detail.\(^9\)

**Current Uses of 3D Printing**

In the past decade, many industries have implemented 3D printing in manufacturing processes or pre-production design stages. 3D Printing is used in both well-established industries, such as automotive, medical, and aerospace, and rising industries, with particularly widespread implementation in consumer products/electronics. According to a Goldman Sachs report released in 2012, 22% of 3D printing revenues came from consumer products/electronics, 19% from automotive manufacturing, 16% from medical/dental products, 13% from industrial/business machines, 10% from aerospace, 7% from academia, 5% from government/military spending, 4% from architectural applications, and 4% from other sources.\(^{10}\) A pie chart of this distribution is shown in Figure 1.1.

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Currently, 3D printing is used largely for rapid prototyping, design engineering, and mass customization. Some industries, such as the aerospace manufacturing, use 3D printing to produce small, complex parts. In addition to common uses in these industries, 3D Printing is transforming small-run production and mass customization manufacturing.

In 2014, the company **Not Impossible Labs** designed and began selling 3D printed prosthetic limbs for a fraction of the traditional cost. One of their products, a prosthetic arm, costs $100 and requires only six hours of machine time to manufacture\(^\text{11}\). Other creative uses for 3D printing include prosthetic limbs for animals, customized chocolate bars, jewelry, and even replacement tissue for damaged internal organs.

Advantages of 3D Printing

3D Printing has several distinct advantages over traditional manufacturing techniques. Some of these advantages include mass customization, complex product manufacturing, toolless product development, and environmentally friendly processing\textsuperscript{12}. In a mass customization environment, manufacturers can make changes to products based on a consumer’s needs. In traditional manufacturing, similar customization requires post-processing, which can be both time-consuming and costly. 3D Printing allows numerous customized products to be manufactured in the same batch. 3D Printers can produce products with intricate geometry that could not be produced by any other manufacturing technique. These products, frequently with functioning internal components, are used commonly in aerospace manufacturing because 3D Printed components can be lighter and stronger than their traditionally manufactured substitutes. In product development, one of the most expensive factors of the design process is the production of tools and dies. With 3D printing, manufacturers can create small-run products without tools or dies. If manufacturers are working on larger scale production designs, engineers can use 3D Printing to create functional prototypes prior to finalizing tool and die design\textsuperscript{13}.


Industry Choice

Although 3D Printing pervades many sectors, I will only analyze three industries in this thesis: the automotive, aerospace, and medical industries. These three industries, which accounted for 45% of the total revenues by end-market in the Goldman Sachs report\(^\text{14}\), share a few common factors that others lack. First, these industries are well established. Second, these industries are well defined. Unlike the category “Consumer Products/Electronics”, which accounts for the greatest percentage of the total revenue by end-market, the automotive, aerospace, and medical fields have definite products and industry goals. Finally, these industries are in the growth stages of their lifespan. This is significant because industries will seek new technologies to minimize costs and continue their profitable growth\(^\text{15}\).

\footnotesize

To analyze the viability of using 3D Printing in the automotive, aerospace, and medical industries, I will create total cost and average cost curves to evaluate the differences in the cost between 3D Printing and other manufacturing techniques. This will be helpful in determining when 3D Printing will be more cost-effective than alternative production means. In this section, I will provide a brief overview of the underlying economic theory, explain the assumptions I consider for this thesis, and create an example to show how I will use these functions to analyze the automotive, aerospace, and medical industries.
Key Assumptions

Before evaluating theories, economists define their key assumptions on which their arguments hinge. For this thesis, my key assumptions include (1) firms want to maximize profit, (2) firms operate in competitive markets for both inputs and outputs, (3) products manufactured by the same firm are perfect substitutes of one another, regardless of their production technique, (4) with the exception of machine cost, all other capital, labor, and opportunity costs are the same, regardless of production technique, and (5) in the cases presented in this thesis, all production costs other than material and machine are negligible.

The purpose of the first assumption is twofold. First, without an assumed rationale for operation, economic principles cannot predict outcomes. Second, the theory that firms maximize profits allows an introduction of the profit equation

\[ \pi = \sum_{i=1}^{n} p y - \sum_{i=1}^{m} w_i x_i \]

where \( \pi \) represents profit, \( p \) represents price, \( y \) represents output, \( w_i \) represents cost, and \( x_i \) represents inputs. This equation shows profit is equal to the summation of revenues minus the summation of costs. The first assumption means that a firm, to maximize profit, will maximize the difference between revenues and costs.

The second assumption allows for an isolation of variables. Based on this assumption, operating in competitive input and output markets implies that the firm is a price taker in both input and output markets. That is, the firm cannot influence the going market prices \( w_i \) or \( p \). If conditions outside the firm change, such as a change in market

demand or market supply, these prices may change. These prices are not under the control of the firm. The combination of these first two assumptions is key in analyzing the total cost function using cost curves.

The third assumption allows for 3D Printing to be used in any application for which alternative manufacturing techniques are currently used. In the real world, this assumption does not strictly hold. In many cases, 3D Printed products have different material limitations than other manufactured products, but with the development of new polymers and additional curing techniques, this difference is diminishing. Furthermore, in some applications, 3D Printed products are preferred, while in other areas, other manufacturing techniques produce superior products. To enable my cost analysis, I will assume that these differences are negligible.

The fourth assumption allows me to isolate machine cost and material cost in my analysis. This assumption is not strictly true. However, in this context, I will assume that the manufacturing company is at a decision point where the management must choose to purchase either a 3D Printer or another piece of machinery to put in a certain space in the floor and use already-employed workers, which allows for this to be a reasonable assumption.

The fifth assumption allows me to assume all other inputs \( x_o^P = 1 \) in the next equation. This allows me to effectively eliminate that factor, allowing an easier derivation to the cost function. In a more complex analysis, an analyst would account for the additional production factors included in the variable \( x_o^P \).

These five assumptions will allow for my cost analysis and comparison between 3D Printing and another manufacturing method. In each industry analysis, I will compare
a currently used manufacturing method with 3D Printing to determine the cost advantages of producing with one method. To understand the comparisons, it is vital to understand the total cost and average cost functions.

The Production Function

When a firm makes a choice, it must consider the associated constraints imposed by customers, its competitors, and technology. For this thesis, I will focus on examining the last of these constraints. Based on technological constraints, only certain combinations of inputs yield outputs, meaning the production output is a function of inputs, or factors of production\(^{17}\).

For my thesis, output \(y\) is a function of material inputs \(x_{\text{mat}}\), machine inputs \(x_{\text{mac}}\), and other inputs \(x_{o}\), such that

\[
y = f(x_{\text{mat}}, x_{\text{mac}}, x_{o})
\]

In my analysis, I utilize a Cobb-Douglas production function that accounts for these variables,

\[
y = Ax_{\text{mat}}^\alpha x_{\text{mac}}^\beta x_{o}^\gamma
\]

where \(A\) is a coefficient that scales with \(y\) and \(\alpha/\beta/\gamma\) are productivity factors. Productivity factors allow a mathematical relationship between increasing one of the inputs and the resulting increase in output. In theory, these could be less than, greater than, or equal to 1. If a productivity factor is less than 1, there are diminishing returns to the variable output. If a productivity factor is greater than 1, there are increasing returns.

to the variable input. Because this function provides that all inputs – other than material – are fixed, the output quantity \( y \) would typically demonstrate the law of diminishing marginal product. This economic law suggests that, although increasing \( x_{mat}^\alpha \) would increase \( y \), it will increase at a decreasing rate, based on the value of \( \alpha^{18} \).

However in this thesis, based on the previous combination of assumptions and the models constructed later, I will assume the productivity factors are equal to 1, which means there are constant returns to the variable input.

There are a few special circumstances concerning the cases presented in this thesis. First, the machines and other inputs scale in fixed proportions with constant returns to scale. For example, if a manufacturer needs \( x_{mac} x_o \) to produce \( y \) units, then the firm would need \( 2x_{mac} 2x_o \) to produce \( 2y \) units. Additionally, as explained in assumption (5), \( x_o \) is negligible between production techniques. In other words, in the cases presented in my thesis,

\[
y = A x_{mat}^\alpha x_{mac}^\beta = B x_{mat}^\alpha
\]

where \( B \) is a constant equal to \( A x_{mac}^\beta \) and \( x_{mat}^\alpha \) is the variable input. I will assume \( x_{mac}^\beta \) scales perfectly with output \( y \), meaning \( x_{mac}^\beta = 1 \) in the cases within my thesis.

Finally, in this thesis, all cases presented consider short run economic restrictions, which allows this equation to represent the production function.

In order to calculate input demand from the production function, I solve the production function for \( x_{mat} \), which identify \( x_{mat} \) as a function of output and the coefficient \( B \). The function

\[ x_{\text{mat}}(y) = \left[ \frac{y^{1/\alpha}}{B} \right] \]

represents input demand for materials as a function of \( y \) and \( B \). In this function, \( x_{\text{material}}(y) \) represents the amount of material needed to produce the desired quantity of \( y \) holding \( x_{\text{mac}} \) and \( x_o \) constant. For the special case of \( \alpha = 1 \), this is the linear function

\[ x_{\text{mat}}(y) = \frac{y}{B} \]

**Total Cost Function**

The total cost function includes the cost of all factors of production, including labor, machine, capital, and opportunity costs. For simplicity, I will assume labor, capital, and opportunity costs are equivalent between 3D Printing and alternative production methods. However, in a more detailed analysis, these costs would likely be non-negligible, e.g., 3D Printers and large machinery may require different amounts of factory floor space or it may take more skilled labor to use complicated machinery. In the previous section, these factors are represented as \( x_o \). Additionally, as explained in the previous section, to create any output in the short run, a firm must use some combination of fixed and variable inputs.

For this analysis, production techniques have unique cost functions comprised of both variable cost and fixed cost. 3D Printing costs include machine, materials, and “other” cost. For each industry, different types of 3D Printers are used, so a more detailed

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estimate of machine cost will follow in each industry analysis. Additionally, materials
cost rates vary with the type of 3D printer. In each industry analysis, a currently used
production technique for a product within that that industry will be analyzed.

Based on these considerations, the total cost can be mathematically represented
by
\[ c(y) = w_{mat}x_{mat}(y) + w_{mac}\bar{x}_{mac} + \bar{w}_o\bar{x}_o \]
where \( w_i \) represents cost per unit and \( x_i \) represents the number of units of each input. To
further define this function, I will manipulate it in two ways. In my analysis, the fixed
cost \( \bar{w}_o\bar{x}_o \) is considered the same regardless of production technique. To simplify the
analysis, I will ignore this term as it does not vary across the different methods. Next, I
will represent \( w_{mac}\bar{x}_{mac} \) with the single term \( F \). This yields the equation
\[ c(y) = w_{mat}x_{mat}(y) + F = c_v(y) + F \]
where \( c(y) \) represents total cost, \( c_v(y) \) represents variable cost, and \( F \) represents fixed
cost. Note, as previously derived, \( x_{mat}(y) = \frac{y}{B} \).

The average cost function, which measures the cost per unit of output, is derived
from the total cost function
\[ c(y) = w_{mat} \frac{y}{B} + F \]
by dividing total cost by the number of units produced, and is represented by the
equation
\[ AC(y) = \frac{w_{mat}}{B} + \frac{F}{y} \]

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where average cost equals the sum of average variable cost and average fixed cost.

By adapting the total cost function, various production techniques can be compared graphically. With the assumptions made here about the production function, \( AC(y) \) decreases as \( y \) increases and is asymptotic to \( y_a \) from above.

**An Example**

To illustrate how I will be analyzing industrial choice, I will construct a simple example. Robert is an entrepreneur who invents a line of hats for dogs and decides he wants to produce and sell these. He wants to make these hats out of plastic. Each hat will weigh .01 pounds. Robert gets equally as much value out of working on an entrepreneurial project as whatever he else he could possibly be doing, so his opportunity costs are negligible. He faces a Cobb-Douglas production function

\[
y_{hats} = f(x_{mat}, \bar{x}_{mac}) = A x_{mat}^{\alpha} \bar{x}_{mac}^{\beta}
\]

where \( \alpha=1 \). This allows, after a similar manipulation as previously shown, for the following derivation of Robert’s cost function

\[
y = A x_{mat}^{\alpha} \bar{x}_{mac}^{\beta} = B x_{mat}^{\alpha}
\]

\[
x_{mat}(y) = \left[ \frac{y}{B} \right]^{\frac{1}{\alpha}}
\]

\[
x_{mat}(y) = \frac{y}{B}
\]

\[
c(y) = w_{mat} x_{mat}(y) + F = c_v(y) + F
\]

\[
c(y) = w_{mat} \frac{y}{B} + F = c_v(y) + F
\]
where his $c_v$ is his material cost, his $(y)$ is his number of units, and his $F$ is his machine cost.

Robert must choose between using a 3D Printer and a 5-Axis Mill. He determines that the best 3D Printer for his company, Banjo’s Hats, is a MakerBot Replicator 2, which costs $1949.00. He also evaluates 5-axis mills and determines that his best choice for a mill would be a Jet 690908 Mill. This mill would cost Robert far more than a 3D Printer, at a total delivery cost of $25,759.00. However, Robert must also evaluate material costs for each of his options. The MakerBot Replicator 2 3D Printer would need to print with MakerBot PLA Filament, available for $36.00 per pound. The mill could use blocks of plastic to mill into shape, available for $1.81 per pound. With these values, the functions

\[ c(y)_{3D\, printing} = \left( \frac{36.00}{\text{pound}} \right) \left( \frac{1}{\text{pound/unit}} \right) (y \text{ number of units}) + 1949.00 \]

and

\[ c(y)_{mill} = \text{cost of mill} + \text{cost of plastic} \]

---


\[ c(y)_{\text{Milling}} = \left( \frac{1.81 \text{ pound}}{\text{unit}} \right) \left( \frac{1 \text{ pound}}{\text{unit}} \right) (y \text{ number of units}) + 25,759.00 \]

represent total cost functions for 3D Printing and milling, respectively. Dividing each of these terms by the number of units yield average cost functions

\[ AC(y)_{3D \text{ Printing}} = (3.60) + 1949.00/(y \text{ number of units}) \]

and

\[ AC(y)_{\text{Milling}} = (0.181) + 25,759.00/(y \text{ number of units}) \]

which will allow Robert to analyze which production technique he should use.

Figure 2.3 and Figure 2.4 shows these functions plotted. As the graph shows, the two manufacturing methods are represented by total cost functions that have far different slopes; the 3D Printing cost function’s slope is nearly twenty times that of the milling cost function.

The most interesting point of this function is unit 6961. At this point, the total cost functions intersect at a total cost of $27,008. Additionally, at this point, the average cost curves intersect at $3.88/unit. From that point onward, the average cost per unit is less for milling than for 3D Printing. For Robert, his decision is clear. Robert should choose a 3D Printer if he thinks he will make 6961 units or fewer. If he were to make more than 6961 hats, his total cost would be minimized with the milling machine.
Figure 2.1: Total Cost Curves of 3D Printing and Milling Banjo’s Hats

Figure 2.2: Average Cost Curves of 3D Printing and Milling Banjo’s Hats
Although it is not vital to understanding a technological analysis for the industry, an examination of the automotive industry will add depth to the evaluation of 3D Printing within it. In this chapter, I will provide a brief introduction to automotive manufacturing history, an examination of its current state, the current and speculated uses of 3D Printers within automotive manufacturing, an evaluation of the costs associated with using 3D Printing in automotive manufacturing, and a short examination of what changes (economically and technologically) are necessary to further the use of 3D Printing in this sector.
The History of Automotive Manufacturing

The automotive industry, rooted in the development of the gasoline engine in the late 1800s, flourished in the twentieth century. Before World War I, the automotive industry was highly diversified with gasoline vehicles, steam-powered engines, and electric cars composing the majority of the market share. Many companies, primarily bicycle manufacturers, carriage manufacturers, and machinery manufacturers, composed small fragments of the total market. After the first decade in the twentieth century, many of the automakers began to cease operation, due to increasing costs and more demand for gas engines.

As demand for automobiles increased, industry leaders sought new, innovative manufacturing techniques to reduce costs. This led to manufacturing revolutions, including interchangeable parts and mass production. Henry Ford, with his assembly line, produced huge numbers of cars at extremely low costs, allowing middle-class households to purchase automobiles.

Concurrently, large-scale businesses within the automotive industry emerged. By 1929, Ford, General Motors, and Chrysler (known as the Big Three) emerged as the industry leaders, composing around 75% of the total market. The Great Depression then furthered the domination of the Big Three. During this period of economic strain, the large automotive manufacturers began to further differentiate their vehicles by


implementing passenger-focused designs, including both aesthetic changes and technical advancements.

World War II pushed the automotive industry even further – from 1945 to 1980, automotive manufacturing increased tenfold, with major growth both within and outside of the United States. Mergers and acquisitions began to fill the market, further reinforcing industry leaders’ standing. However, other countries began to host strong competitors. As this competition intensified, automobiles became works of design and technological art.

Today, the automotive industry represents more than one fourth of the entire United States’ retail trade by revenues. Manufacturers are currently transitioning to more environmentally friendly, cheaper, safer, customizable cars. With the advancements happening every day in the automotive industry, 3D Printing could become a vital manufacturing technique within the industry.

**Automotive Production in the United States**

The automotive industry began in the late 1890s with the creation of the first automobile. Shortly after the invention, the United States began dominating the market. By 1929, the United States had produced more than ninety percent of the 32 million automobiles. The United States maintained dominance until the 1980s, at which point Japan overtook the U.S. as the world’s largest automotive manufacturer. In the past thirty

years, the U.S. and China both increased production to levels greater than Japan. As of the second quarter of fiscal year 2014, the United States is the second largest automotive manufacturer, producing almost 6 million units in the quarter.

The automotive industry (including dealerships) accounts for about 3.5% of the U.S. GDP, employs 786,000 people, and generates $225.2 billion of supplier industry shipments. Within the automotive industry, a few large firms dominate. Vehicles produced by General Motors, Ford, Chrysler, Toyota, Honda, and Nissan accounted for 77.7% of the total United States automotive sales in the first two fiscal quarters of 2014.

By combining the immense financial resources available with a large consumer market, skilled labor force, and government incentives, the U.S. automotive industry is poised to lead the world in automotive innovation. Current industry goals include increased fuel economy, higher performing components, and product differentiation.

**Current Uses of 3D Printing in the Automotive Industry**

Many automotive manufacturers use 3D Printing in various stages of production, ranging from basic rapid prototyping to rapid manufacturing and tooling. Based on the variety of uses and the varying level of involvement of 3D Printing, SmarTech Markets

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developed a four-stage model to analyze adoption of 3D Printers, recreated in Figure 3.1.

Each stage involves various uses of 3D Printing. According to SmarTech, in Stage 1, automotive manufacturers utilize low volume and basic design prototyping, often from a single printer. These prototypes are used to reduce costs and speed development processes. Many automotive manufacturers entered Stage 1 as early as 2008. Stage 2, which usually follows as a transition from Stage 1 to Stage 3, involves the use of multiple 3D Printers throughout engineering teams to encourage creativity or to produce multiple iterations of a single prototype quickly before finalizing design. After adoption of 3D Printers into Stage 2, many companies quickly transition to Stage 3,

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where 3D Printers are used to create functional prototypes for test or concept models. These prototypes frequently have similar functionality to final products. Additionally, when companies are in this stage of adoption, 3D Printers begin to span outside of design engineering into cross-organizational engineering groups. In this stage, many companies explore using multiple types of 3D Printers, 3D Printed products as end parts, and 3D Printed metal parts. According to SmarTech, Most large automotive manufacturers are currently in this stage of 3D Printing adoption. In Stage 4, companies integrate 3D Printers and 3D Printed products into their production lines, either as tooling or in direct production of end use parts. The vast majority of the top automotive manufacturers are either in Stage 1 or Stage 3. Currently, primarily performance motorsports and racecar makers exist in Stage 4 of adoption, but their success may lead to the large manufacturers to venture into the space.

As of 2014, automotive manufacturers are using 3D Printers to manufacture over 100,000 parts annually, including a few production parts, many prototypes, and a variety of custom hand tools and fixtures. One of the most innovative uses for 3D Printed products in automotive was in the Strakka Dome S103 racecar, which competed in the Le Mans 24 hour race in October 2014. This past year, about 5% of the racecar was 3D Printed, including the dash panel, the brake duct, and dive

panels. Although Stakka had previously only used 3D Printing for prototyping, the company's engineers adjusted their approach and adopted the technology. Dan Walmsley, one of Stakka's engineers, commented, “We had to go through a bit of a mindset shift.... Whilst we've probably underutilized [3D Printing] on this car, in the future you're going to see cars with a much higher proportion of it.” Dan Walmsley thinks Strakka will use 3D Printed parts for 80% of the vehicle in the next five to ten years.

Automotive manufacturers commonly use 3D Printers for product development and prototyping. For example, Ford uses the technology in defect elimination and product design. In 2010, Ford avoided a costly, four month delay in releasing the Ford Explorer by using 3D Printing to diagnose and fix a brake-noise issue discovered shortly before the line launched. Ford uses the technology similarly to other automotive manufacturers. While this is not necessarily ambitious, engineers are beginning to accept 3D Printing as a legitimate manufacturing technique, which should lead to widespread adoption.

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Potential Uses of 3D Printing in the Automotive Industry

Many speculators believe that the production of end use 3D Printing hinges around the development of more advanced metal alloys, high performance thermoplastics and other advanced materials. Additionally, the cost of materials used in 3D Printing must drastically decrease to rival other production techniques. With some of these technological advances, 3D Printed components could replace small or complicated pieces made with other manufacturing techniques. Eventually, if significant strides were made in material technologies, perhaps 3D printing could even replace other large component manufacturing techniques, such as stamping and welding.

Cost Analysis of 3D Printing in Automotive Manufacturing

3D Printing could be used to make engine blocks. Although this is not a current use of 3D Printing, it is a realistic concept with the evolving technology, particularly in low-run models. Using the cheapest available 3D Printer and using the smallest possible manufacturing line setup, the cost curves of producing an engine block provide an interesting depth to this potential. In this section, I will analyze the production of a Ford Mustang Engine block. This component weighs 105 pounds and is 302 cubic inches in volume. I will use these numbers in the following calculations.

To analyze production of an engine block, I will assume the production function is similar to the example from Chapter II: Underlying Economic Theory. A manufacturer producing engine blocks realizes a Cobbs-Douglas production function where there are constant returns to variable inputs. The output is a function of inputs such that

\[ y = A x_{mat}^{\alpha} x_{mac}^{\beta} = B x_{mat}^{\alpha} \]
where $B = \alpha x^\beta_{mac}$ and $x_{mat}(y)$ represents the material inputs. By solving for $x_{mat}(y)$,

$$x_{mat}(y) = \left[ \frac{y^\frac{1}{\beta}}{B} \right]$$

By recognizing $\alpha = 1$ due to the assumption that there are constant returns to scale,

$$x_{mat}(y) = \frac{y}{B}$$

Following this derivation, I can calculate the cost function

$$c(y) = w_{mat} x_{mat}(y) + F = c_v(y) + F$$

and by substituting $\frac{y}{B}$ for $x_{mat}(y)$ in this equation, I find the cost function

$$c(y) = w_{mat} \frac{y}{B} + F = c_v(y) + F$$

From this function, I can derive the average cost function

$$AC(y) = \frac{w_{mat}}{B} + \frac{F}{y}$$

by dividing the total cost by the number of units produced. I will use the cost function and average cost function to analyze engine block production techniques.

Currently, engine blocks are produced using sand-casting. This method is a long, complicated process involving a series of machining and die-casting. This process requires multiple robotic arms, casting presses, a jet melter, heating machines, and injection pumps\(^{43}\). To set up the line at minimum expense, a manufacturer would need three robotic arms costing $3999.99 each\(^{44}\), a sand molding machine costing $6,750.00\(^{45}\),

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\(^{43}\) Identified from “How It’s Made: Engine Blocks” <https://www.youtube.com/watch?v=yXVLbzI3xTE>.

\(^{44}\) A capable robotic arm varies in pricing significantly. At the time of writing, a used robotic arm was available on ebay for $3999.99 at <http://www.ebay.com/tm/Kuka-Roboter-KR100P-2-Robot-Arm-w-KRC1A-Controller-and-Teach-Pendant-271597116926>. For the purpose of this process, I am going to assume this is market value.
a jet melter costing $8000, and a pump costing $4995.00\textsuperscript{46}. Materials used in the process
would be foundry sand costing $149.00 per 100 pounds of sand\textsuperscript{47}, binder costing $82.00
per gallon\textsuperscript{48}, and eighty-two 1.6-pound aluminum ingots costing $495.28 ($6.04 per
ingot)\textsuperscript{49}. All of these materials will be consumed when producing an engine block. These
input costs yield the cost function
\[ c(y)_{\text{Sand casting}} = \left( 3 \text{ robotic arms} \times \frac{$3999.99}{\text{robotic arm}} \right) + (1 \text{ sand molding machine} \times \frac{$6750.00}{\text{sand molding machine}}) + (1 \text{ jet melter} \times \frac{$8000.00}{\text{jet melter}}) + (1 \text{ pump} \times \frac{$4995.00}{\text{pump}}) + (100 \text{ pounds of sand} \times \frac{\$1.49}{\text{pound of sand}}) + (1 \text{ gallon of binder} \times \frac{\$82.00}{\text{gallon}}) + (82 \text{ ingots} \times \frac{\$6.04}{\text{ingot}}) \]

which can be simplified to
\[ c(y)_{\text{Sand casting}} = $23,744.99 + $726.28(y) \]

and which can be used to derive the average cost function
\[ A_c(y)_{\text{Sand casting}} = \frac{23,744.99}{y} + $726.28 \]

\textsuperscript{46} Available from HiTemp at <http://hitemp.com/quickpump/>.
\textsuperscript{49} Available from Roto Metals <http://www.budgetcastingsupply.com/product-p/1025-gal.htm>
I will return to these two functions shortly, after a discussion of 3D Printing engine blocks.

Currently, 3D Printers could compete with the costs of sand-casting for a small number of units, depending on what type of 3D Printer the manufacturer purchased. For this analysis, I will assume the manufacturer uses the cheapest sufficient 3D Printer available, a new printer from Aurora Labs that costs $4000.00\textsuperscript{50}. There is a caveat to this assumption – Aurora Labs is launching their first line of 3D Printers in 2015. The launch may reveal that the machines have less capacity than claimed. For production material, I will assume that the manufacturer will use material from Aurora Labs to match the printer, although it is more expensive than some other options. Material from Aurora Labs costs at minimum $184.38 per 5kg\textsuperscript{51}. The 105-pound engine block will require 95.25\% of ten lots of material, meaning the manufacturing material will cost $1756.29 per unit. This yields the cost function

$$c(y)_{3D\, printing} = $4000.00 + (10 \, 5kg\, blocks \times \frac{$184.38}{5kg\, block}) (y)$$

and the average cost function

$$AC(y)_{3D\, printing} = \frac{$4000.00}{y} + $1756.29$$

As discussed in Chapter II: General Economic Theory, these four functions can be graphed on the same axes, revealing several points of interest. Figure 3.2 shows the cost functions and Figure 3.3 shows the average cost functions for the two methods of

\textsuperscript{50} Available from Aurora Labs <http://auroralabs3d.com>.
\textsuperscript{51} Available currently through the Aurora Labs website <http://shop.auroralabs3d.com/products/all-metal-powders-5-kg?variant=1001009055>.
producing engine blocks. The intersection of the cost functions and the intersection of the average cost functions reveal the decision points.

As shown in **Figure 3.2** and **Figure 3.3**, the cost functions intersect shortly after the nineteenth unit. Prior to this point, 3D Printing engine blocks yielded a lower average cost per unit. After the nineteenth unit, using sand-casting to produce engine blocks yields a lower cost per unit. If a manufacturer could choose only one production technique and the manufacturer intended on producing more than nineteen units, the manufacturer should invest in a sand-casting production line.

There are a few technological improvements to 3D Printing material that would alter the slope of the cost function for producing using 3D Printing. For every percentage decrease in the price of the 3D Printing material, the slope of the cost function would decrease by one percent. For example, if 3D Printing material became 25% cheaper, the cost function’s slope would also decrease by 25% and move the intersection of the cost functions to slightly past the thirty-third unit. Ultimately, for 3D Printing to be strictly preferred to sand-casting, the material cost would need to be reduced by 60%. However, although this will not happen short term, it is within the realm of possibility for the future. A detailed comparative statistical analysis would provide much more insight into the future of 3D Printing, but is outside of the scope of this project. Future researchers can analyze how input price changes would change intersection points.
Figure 3.2: Derived Engine Block Total Cost Curves

Figure 3.3: Derived Engine Block Average Cost Curves
In addition to comparing cost functions, revisiting the assumptions from Chapter II: General Economic Theory is important. Assumption (1) must not be loosened – without assumption (1), it is impossible to determine what would motivate a company to manufacture engine blocks. Reexamining assumption (2) allows the last discussion in the previous paragraph – although input prices, including 3D Printing raw material, are fixed, this is a short run perspective. Examining assumption (3) in the context of engine blocks reveals the most interesting commentary. Engine blocks produced on a $4000 3D Printer are not perfect substitutes for traditionally manufactured parts. In sand-casting, operators have input into the quality of the finished component by interacting with the manufacturing process and doing post-process machining. Although 3D Printed engine blocks could be post-processed, the concept complicates the model. Additionally, this consideration leads to reexamining assumption (4) and (5). The labor, capital, and opportunity costs between the two are not equivalent. Operators machining engine blocks require many more specialized skills than operators interacting with 3D Printing. The space in a factory required to set up a sand-casting line is many times more than the space required for a 3D Printing operation. These two costs create haziness when comparing the costs and benefits between the two manufacturing techniques. However, for the purposes of this thesis, these assumptions are true. As is, with assumptions (1-5) in place, 3D Printing would have lower costs for the first nineteen units of production.
Necessary Changes for Increased Use of 3D Printing

As discussed previously, for 3D Printing to be used in engine block manufacturing, material costs would need to decrease by about 60%. Additionally, 3D Printer quality must improve so that 3D Printed products and other products are perfect substitutes of one another. In addition to these, there are a variety of other changes that would propel 3D Printing to universal adoption.

One key non-technological adjustment would create significant momentum for 3D Printing. If automotive engineers adjusted their mindset and embraced 3D Printing as a viable technique to create parts, 3D Printing would become an integral component of production vehicle manufacturing. Scott Dunham, a Senior Business Analyst at SmarTech Markets, writes\(^\text{52}\):

“In order to get to the pinnacle of 3D printing adoption in automotive, users have to learn how to utilize additive fabrication to positively affect the three major trends driving automotive manufacturing of tomorrow – increased fuel economy, higher performance components, and product differentiation. Today’s 3D printers are capable of enhancing all of these areas, but it may take some time for automotive manufacturers to really alter automobile design processes to truly embrace additive technology.”

This analysis provides insight into the issues with 3D Printing in automotive manufacturing – engineers must embrace the technology in lieu of considering it simply a prototyping technique. Considering 3D Printers are currently capable of producing parts with tolerances specific enough to satisfy automotive manufacturers, 3D Printer advocates need to relay a thorough message of what 3D Printing can do. Perhaps, with enough promoting, 3D Printing could permeate throughout the industry. As a

manufacturing technique, 3D Printing has the potential to deliver significant cost savings while achieving the three major current goals of automotive manufacturers. Due to this advantage, the automotive industry should adopt 3D Printing as an integral manufacturing technique in the next decade.
IV
The Aerospace Industry

As in the automotive section of this thesis, familiarity with the aerospace industry is not vital to understanding the analysis section, but will add significant meaning to the results. In this chapter, I will provide a brief introduction to the history of the aerospace industry, an examination of its current state, the current and speculated uses of 3D Printers within aerospace manufacturing, an evaluation of the costs associated with using 3D Printing in aerospace manufacturing, and a short examination of what economic and technological changes are necessary to further the use of 3D Printing in this sector.
The History of the Aerospace Industry

The aerospace industry encompasses a large range of manufacturers, including manufacturers who produce airplanes, helicopters, military aircraft, missiles, rockets, spacecraft, and satellites. This industry dates back to the end of the 1700s, when Joseph Montgolfier first discovered he could lift balloons with hot air. Although this is considered the start of the aerospace industry, the first major advancement occurred at the end of the nineteenth century, when a German inventor name Otto Lilienthal built bird-like wings and demonstrated that heavier-than-air flight was, in fact, possible for man. This work inspired Orville and Wilbur Wright, who began working on flight in 1899\(^5\).

In 1906, after more than one hundred successful flights, many articles were published hailing the Wright brothers’ achievements\(^5\). From that point, the aerospace industry advanced exponentially, due to government-backed development and increasing notoriety. By the end of World War II, jet engines replaced propellers. Within another ten years, airplanes reached supersonic speeds. Less than a decade later, multiple countries sent astronauts into space. Since the 1960’s, the aerospace industry has developed into a heavily regulated, diverse, enormous industry.


The Aerospace Industry in the United States

The United States supports the largest aerospace sector in the world, attracting foreign firms to the nation with its skilled workforce, complex distribution systems, and strong governmental support. In 2012, the U.S. aerospace sector contributed $118.5 billion (64.3% of domestic aerospace production) in export sales to the U.S. economy. This yielded a positive trade balance of $70.5 billion, which is the largest of any manufacturing industry. Additionally, U.S. aerospace exports directly and indirectly account more jobs than any other export commodity, directly supporting about 500,000 workers in scientific and technical jobs and more than 700,000 jobs in related fields.

The aerospace sector is composed of a diverse group of subsectors. These include Large Civil Aircraft, Commercial Space, General Aviation, Engines, Unmanned Aircraft Systems, Airport Infrastructure/Aviation Security, Alternative Aviation Fuels, and Supply Chain. The subsectors encompass many products, such as hot air balloons, unmanned aircraft, small planes, passenger jets, and spacecraft. The diversity of products contributes to the strong industry position within the U.S. Additionally, federal programs and legislation support the aerospace industry by incentivizing private space exploration and transportation, guiding research and development, and setting regulations on exportation.

The United States, with a skilled labor force, favorable government incentives, and immense investing culture, can maintain its status as a world leader in aerospace

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manufacturing. In this position, the industry is poised to achieve many new feats, including dramatically increased fuel efficiency and successful space exploration.

3D Printers in The Aerospace Industry

The aerospace industry adopted 3D Printing as a legitimate production technique before most other industries. Similar to the automotive industry, aerospace manufacturers use 3D Printing in various stages of production, ranging from basic rapid prototyping to rapid manufacturing and tooling. Based on SmarTech’s four-stage model, shown in Figure 3.1 and recreated as Figure 4.1, there are aerospace manufacturers in every stage of 3D Printer adoption.

![Figure 4.1: The Stages of Adoption for 3D Printing in the Aerospace Industry](http://3dprint.com/wp-content/uploads/2014/12/ms.png)

Each stage involves the range of use of 3D Printing. In Stage 1, aerospace manufacturers use 3D Printers to utilize low volume and basic design prototyping. Prototypes in this stage generally reduce costs and speed development processes. In the aerospace industry, GE became one of the first large companies to enter the first stage of 3D printing adoption sometime before 2010\(^59\). Although the specific date is unavailable, speculators believe the firm purchased a 3D Printer around 2006 when the technology cost nearly $400,000 per printer. The first time GE publicly announced its experimentation with additive technology was in 2008, in a short podcast about their manufacturing\(^60\). Stage 2, which is considered a transition stage, involves the use of multiple 3D Printers throughout engineering teams to encourage creativity or to produce multiple iterations of a single prototype quickly before finalizing design. Most aerospace manufacturers have already transitioned through this stage of adoption into Stage 3 or Stage 4. In Stage 3, manufacturers use 3D Printers to create functional prototypes for test or concept models. In aerospace manufacturing, many firms entered this stage of adoption around 2012, which led to the early transition to Stage 4. In Stage 4, companies integrate 3D Printers and 3D Printed products into their production lines, either as tooling or in direct production of end parts\(^61\). Because 3D Printed parts are most cost-efficient in low-run production environments, the aerospace industry fosters 3D Printer adoption.


GE, by opening a mass additive manufacturing facility to produce 3D Printed fuel nozzles for LEAP jet engines, propelled 3D Printing into the forefront of the aerospace industry. Rolls-Royce, to compete with GE, announced in February 2015 that it will flight-test what it claims to be the largest 3D Printed aerospace component ever – a titanium structure in its Trent XWB-97 engine\(^\text{62}\). Another aerospace leader, Boeing, manufactured over 22,000 parts with 3D Printing during 2014\(^\text{63}\). With these advances and similar innovations from competing firms, 3D Printing is staged to achieve exponential growth in the next few years.

**Potential Uses for 3D Printing in the Aerospace Industry**

Recent advances in 3D Printing promise further adoption into the aerospace industry. In February of 2015, Australian researchers at Monash University unveiled a 3D Printed jet engine\(^\text{64}\). Hailed as an engineering breakthrough, this product can lead to cheaper, lighter, and more fuel-efficient jets. Since the announcement, huge aerospace firms, such as Airbus, Boeing, and Raytheon, have traveled to examine the Australian product.

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According to technology consulting firm **ICF International**, 3D Printed parts will generate almost $2 billion in revenue within the next decade. Potential applications include aircraft wings, complex engine parts, on-demand parts in space, and unmanned aerial systems. Soon, without many technological advances in 3D Printing, the technology will ubiquitously transform the aerospace industry.

**Cost Analysis for 3D Printing in the Aerospace Industry**

**GE Aviation** uses 3D Printed fuel nozzles on their CFM LEAP engines. GE projects building more than 85,000 fuel nozzles – based on the previous automotive engine block analysis, manufacturing this many components seems like it would render 3D Printing impractical.

I will construct a cost function similar to the engine block production cost function by following the same steps from *Chapter II: Underlying Economic Theory*. A fuel nozzle manufacturer realizes a Cobbs-Douglas production function where there are constant returns to variable inputs. The output is a function of inputs such that

\[ y = A^\alpha x^\beta_{mat} = B x^\alpha_{mat} \]

where \( B = A^\beta x_{mac} \) and \( x_{mat}(y) \) represents the material inputs. By solving for \( x_{mat}(y) \),

\[ x_{mat}(y) = \left[ \frac{y}{B} \right]^{\frac{1}{\alpha}} \]

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By recognizing $\alpha = 1$ due to the assumption that there are constant returns to scale,

$$x_{mat}(y) = \frac{y}{B}$$

Following this derivation, I can calculate the cost function

$$c(y) = w_{mat} x_{mat}(y) + F = c_v(y) + F$$

and by substituting $\frac{y}{B}$ for $x_{mat}(y)$ in this equation, I find the cost function

$$c(y) = w_{mat} \frac{y}{B} + F = c_v(y) + F$$

From this function, I can derive the average cost function

$$AC(y) = \frac{w_{mat}}{B} + \frac{F}{y}$$

by dividing the total cost by the number of units produced. I will use these cost functions to analyze engine block production techniques.

The traditional fuel nozzle is a metal subassembly consisting of eighteen different components\textsuperscript{67}. To create these eighteen parts, the die-casting process requires a unique die for each component, a jet melter, and injection pumps. After manufacturing the parts, an operator would need to assemble the fuel nozzle subassembly\textsuperscript{68}. To set up the production line at minimum expense, a manufacturer would need a pump costing $4995.00\textsuperscript{69}, a jet melter costing $8000, and a unique die for each component. The manufacturer would have to create eighteen dies to manufacture the various components. According to an online estimator, the total cost to set up a single die-cast procedure


\textsuperscript{69} Available from HiTemp at ⟨http://hitemp.com/quickpump⟩.
would be $33,195\textsuperscript{70}, but by using the same jet melter and pump with each process, this
cost goes down to about $20,200 per die. To produce each component, the manufacturer
would need raw stainless steel, which costs $1.81 per pound\textsuperscript{71}. The total weight of the
component is 1 lb. These prices yield the cost function

\[
c(y)_{\text{Die casting}} = \left(19 \text{ casting dies} \times \frac{\$20,200.00}{\text{casting die}}\right) + \left(1 \text{ pump} \times \frac{\$4995.00}{\text{pump}}\right) + \left(1 \text{ jet melter} \times \frac{\$8000.00}{\text{jet melter}}\right) + \left(1 \text{ pound of steel} \times \frac{\$1.81}{\text{pound}}\right)y
\]

which can be simplified to

\[
c(y)_{\text{Die casting}} = \$396,795 + 1.81y
\]

and which can be used to derive the average cost function

\[
AC(y)_{\text{Sand casting}} = \$\frac{396,795}{y} + 1.81
\]

I will return to these two functions shortly, after a discussion of 3D Printing fuel nozzles.

The 3D Printed fuel nozzle requires a single 3D Printing process and no
subassembly. 3D Printing reduces weight by 25%, eliminates the need for a subassembly
operation, and allows the part to have more intricate internal geometry\textsuperscript{72}. For this
analysis, I will assume that the manufacturer will use the same 3D Printer and materials
that were analyzed for the engine block. Based on this information, the printer will cost
$4000.00 and material will cost $184.38 per 5kg. Based on the traditional component’s

\textsuperscript{70} "Cost Estimator." Die Casting. Web. 23 Feb. 2015. \\

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weight and the 25% reduction, the 3D Printed product weighs about 0.75 pounds – which means the material for the fuel nozzle will cost about $12.54 per unit. This yields the cost function

\[ c(y)_{3D\,\text{Printing}} = \$4000.00 + (0.75 \text{ pounds} \times \frac{\$16.72}{\text{pound}})(y) \]

and the average cost function

\[ AC(y)_{3D\,\text{Printing}} = \frac{\$4000.00}{y} + 12.54 \]

As discussed in *Chapter II: General Economic Theory* and conducted in the automotive engine block analysis, these four functions can be compared graphically, revealing points of interest. *Figure 4.2* and *Figure 4.3* show the cost functions and average cost functions for the methods of production. The intersection of the cost functions and the intersection of the average cost functions reveal interesting points.
Figure 4.2: Derived Fuel Nozzle Total Cost Curves

Figure 4.3: Derived Fuel Nozzle Average Cost Curves
As shown in Figure 4.2 and Figure 4.3, the cost functions intersect somewhere between the 30,000th unit and the 40,000th unit on the graph. The point of intersection is after the 36,607th unit. After this unit, using the previously stated inputs, the die-casting process is less expensive than 3D Printing. If a manufacturer can choose only one production technique and the manufacturer intended on producing more than 36,607 units, the manufacturer should invest in a die-casting line. If a manufacturer plans on producing fewer than 36,607 units, the firm should install a 3D Printing operation.

However, it is important to examine this comparison in context of its real world application and its reliance on the assumptions from Chapter II: General Economic Theory. GE is currently using 3D Printing to produce its 80,000 fuel nozzles – why? There are a few possible explanations. The first and most likely is some sort of mathematical inaccuracy; there is a high chance that some variable is either overestimated or underestimated or that one of the variables accounted for in second assumption adds cost to the die-casting procedure (such as labor expenses used to assemble the subassembly). In this same vein of error, GE could probably purchase raw 3D Printing materials in bulk for significantly cheaper than a regular consumer could.

The next possible (but less likely) explanation hinges on the first assumption; there may be a non-financial profit gained from using 3D Printing in production – perhaps, GE benefits from their market perceiving the product as “innovative” or “futuristic”, both common adjectives associated with 3D Printing. Another possible explanation involves loosening the third assumption– there are mechanical benefits realized from using a 3D Printed product. As stated earlier, the 3D Printed fuel nozzle has a more intricate internal geometry and weighs less, both of which could increase value to the customer. If value to
the customer increases, GE’s revenue could increase, perhaps offsetting the increase in production expense. However, with the stated assumptions and the variables defined previously, 3D Printing would only have a lower cost for the first 36,607 units of output.

**Necessary Changes to Expand Aerospace 3D Printing**

Few, if any, things need to change for increased adoption of 3D Printing within the aerospace industry. Further developments will allow firms to realize greater cost reductions from 3D Printing, but significant savings already exist. According to American Airlines, for every pound of weight removed from the aircraft, the company saves 11,000 gallons of fuel annually – and additive manufacturing can drastically reduce component weight\(^\text{73}\). Industry experts attribute the sudden inclination of aerospace leaders toward 3D Printing to this fact.

An industry analysis conducting by PwC suggests the limiting factors for universal adoption in the aerospace industry are product quality limits and slow processing speeds\(^\text{74}\). The more pressing of these two issues is the processing speed – while parts require days to complete, firms are limited to using 3D Printing sparingly. Figure 4.3 shows an adoption map from 2013 that relates the quantity of parts to the per

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unit process speed\textsuperscript{75}. As shown in Figure 4.4, once additive manufacturing technology progresses to the stage where it can produce thousands of parts per day, it will probably be used to produce a much larger mix of components. This map is already two years old – as mentioned previously, some parts of aircraft engines and commercial planes are already being produced using 3D Printing\textsuperscript{76}.

With imminent advances in materials and production speeds, 3D Printing will spread even further throughout the aerospace industry, becoming an integral part of the manufacturing production. Based on the cost saving potential, within the next decade, most aerospace manufacturers should use 3D Printing for production parts.

\textbf{Figure 4.4: 3D Printing Adoption Map}

\textsuperscript{75} "3D Printing: A Potential Game Changer for Aerospace and Defense." 

\textsuperscript{76} "3D Printing: A Potential Game Changer for Aerospace and Defense." 
The medical industry has a diverse range of products and services. The medical industry uses 3D Printers completely differently than the automotive or aerospace industries. To understand how the uses have developed, a reader needs a broad overview of the history and current state of the medical industry. This chapter will provide that overview, followed by an examination of how 3D Printers are being used to revolutionize the medical industry, an evaluation of the costs associated with using 3D Printing in the medical industry, and a short examination of the future for 3D Printing within the industry.
The Medical Manufacturing Industry

The medical equipment and device manufacturing industry produces a wide range of products, including tools that diagnose, monitor, and treat conditions and illnesses. The products range from simple, inexpensive tools to multimillion-dollar machinery. Additionally, the medtech industry includes software products, but this thesis will not focus on non-manufactured goods.

Although tools have been used throughout human history to help treat illnesses, the medical equipment and device manufacturing industry began sometime in the mid-nineteenth century, when the medical profession became regulated and physicians began to seek consistency and reliability in equipment. Since 1900, the average life expectancy has increased from 47 years to greater than 78 years – an increase largely attributed to advances in medical technology.

Today, more than 1000 medtech companies thrive in the United States, with the industry valued at more than $110 billion in 2012. However, a changing political landscape will affect the medical industry during the next decade. Prominent healthcare debates during the past few years lead to doubts for the future profitability of the industry. According to several industry analyses, continued success hinges on technological innovations – which, perhaps, 3D Printing will deliver.

Uses of 3D Printers in the Medical Industry

Currently, 3D Printers are used in a variety of applications throughout the medical industry. The most common uses involve printing dental devices and implants, models of individuals’ bodies for pre-surgery practice, and “replacement body parts” (such as prosthetics or replacement segments of bones)\(^80\). These uses are quite different from the implementations in the automotive and aerospace industries – an adoption map similar to the ones in the previous chapters would not accurately represent the uses of 3D Printing in medical manufacturing. Instead of exploring a similar adoption map, this section will examine eleven current applications of 3D Printing in the medtech industry.

3D Printing can be used to create swatches of tissues out of skin cells with interwoven structural material. In early 2014, researchers at Harvard University created a patch of tissue containing skin cells and biological structure material interwoven with blood-vessel-like structures\(^81\). By lining the channels with a patient’s blood cells, the team expects to be able to create actual replacement tissues and organs. The research team used a custom-built four nozzle 3D printer with a special material – one that liquefies as it cools – to construct the tissue.

Due to the mass-customizability of 3D Printed products, prosthetic limbs fit to individuals are manufactured using 3D Printing. The most important aspect of 3D Printing prosthetics is the cost saving – using open source design files, a Johns Hopkins

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research team has created a $50 prosthetic hand. Commercially made prosthetics can cost anywhere between $30,000 and $50,000\(^8\).

Researchers at Louisiana Technical University recently printed biocompatible, biodegradable devices for delivering bone cancer medicine delivery devices. The research, focused on the production of anti-infective and chemotherapeutic filaments that can then be molded into discs, beads, catheters, etc., determined that 3D Printing medicine-delivery capsules could permit clinicians to provide medicine with patient-specific dosing\(^9\). The filament produced successfully delivers drugs in a patient’s body and then dissolves\(^1\). This advance should help fight bone cancer in the near future, after the new medicine passes rigorous testing procedures.

Many hospitals are using 3D Printed models of patient-specific organs to practice complex surgeries, drastically increasing surgery success rates. For example, recently, in Sao Paulo, Brazil, Dr. Jose Carlos Barbi Goncalves performed a surgery on a twelve year old that developed a tumor adjacent to his spinal column. Determined inoperable, the tumor neighbored the spinal column, several arteries, and the boy’s kidneys. With the help of the Tridimensional Technologies Division of the Center for Information

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Technology Renato Archer, the team created 3D models of the boy’s tumor and managed to, after a few practice runs, successfully remove the tumor\textsuperscript{85}.

In 2011, Professor Susmita Bose of Washington State University printed intricate scaffolding that promotes bone growth into a desired shape. Using a 3D Printer, the researcher created a structure to attach to actual bone. With the structure in place, the existing bone grows over the scaffolding. After a few weeks, the scaffolding dissolves, leaving the patient’s new bone in place. With this technology, doctors can treat osteoporosis and broken bones. Bose reported successful in vitro tests in 2011 and has continued further testing and research since then\textsuperscript{86}.

Cornell University’s Jonathan Butcher 3D Printed a heart valve using a dual-syringe machine, which will soon be tested in sheep. By designing a precise geometric pattern mimicking the heart valve’s dimensions and using a hydrogel material, Butcher’s team created a manufactured product similar to the natural occurring one – a key to preventing patient rejection. Butcher believes tissue engineering will become and integral part of the biomedical community within the next few years\textsuperscript{87}.

Another Cornell researcher, Lawrence Bonassar, used 3D Printing to create intervertebral discs that treat major spinal conditions. The team uses patient’s cells to fill


3D Printer disc segments, preventing rejection when implanted into the patient’s spine. The team hopes to treat lower back pain issues with these implants. In 2014, the team tested the technology on rats. According to Bonassar, the team still needs to conduct further research before testing the implants on humans, but the tests were promising.

Poverty-stricken areas of the world use 3D Printed medical devices in surgeries due to their inexpensive production and ease of access. For example iLab//Haiti brought two 3D Printers to Haiti, where the company manufactures products needed by local medical clinics. Their first product, 3D Printed umbilical cord clamps, has helped numerous families in the impoverished country. In the future, iLab plans to create outposts in more countries to help people who need support.

Three teams of doctors – in China, the Netherlands, and Slovakia – have replaced sections of skulls with 3D Printed replications to repair bone and brain damage. During the surgery at the University Medical Center in Utrecht, Netherlands, a team completed the first-ever full skull transplant on a woman suffering from a condition that thickens the skull’s bone structure, damaging the brain. The successful transplant promises wider adoption in the future.

James Yoo, a researcher at the Wake Forest School of Medicine developed a 3D Printer capable of printing skin straight onto wounds for burn victims. Motivated by the

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injuries occurring in the war in the Middle East, Yoo’s research team built a bioprinter than scans a wound, determines the depth and area of the injury, and prints several layers of skin cells to restore the area to its original state. The technology has successfully passed through animal testing and can progress to human burn victims sometime in the near future

Medtech company **Organovo** recently announced a commercial launch for their bio-printed liver segments that can function in humans for around 40 days. **Organovo**, the pioneer of the 3D bioprinting business, has researched the possibility of printing livers since 2007. In 2014, the company announced a soon-to-be commercially available liver that will allow pharmaceutical manufacturers to test products. Although the full livers are not yet ready to function in humans, the technology is coming – **Organovo** wants to help solve the organ supply shortage throughout the world using its technology

Although the 3D Printing implementations discussed span the medical industry, this thesis only describes a few of the uses. As shown in this section, 3D Printing has already transformed the medical industry. With these advances in mind, a reader can only imagine the future that is possible with additive manufacturing technology.

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Cost Analysis of 3D Printers in the Medical Industry

Because 3D Printed technology is used so differently in the medical industry than the automotive and aerospace industries, this analysis section is different than the other two. In this section, I will analyze the cost of manufacturing a soft tissue prosthetic ear based on per unit cost. I will not construct cost functions nor compare cost curves.

Traditionally, silicon ears are handmade, requiring between five and seven hospital visits for a patient and between five and ten weeks to fabricate. A traditionally manufactured silicon ear costs up to $4000\(^{93}\). To create a silicon ear, few machines are necessary; the cost largely stems from materials and labor. Based on this information, I will assume that handmade silicon ears have a constant marginal cost of $4000.

Silicon ears manufactured using an SLA 3D Printer would require a total of 187.2 cm\(^3\) of material at a cost of about $2.20 per cubic centimeter\(^{94}\) of material. Using these values, a 3D Printed prosthetic ear would have a constant marginal cost of $411.84. Because SLA 3D Printers are some of the cheapest ones (with prices as low as $200 for a basic machine) and the marginal cost for a printer ear is far less than the marginal cost for a handmade ear, the first and each subsequent printed ear would be cheaper than a handmade prosthetic. This technology, which is already in place, costs far less than the traditionally manufactured alternative.

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The Future of 3D Printing in the Medical Industry

As the previous examination of the uses of 3D Printing in the medical industry illustrates, additive manufacturing technology can be used in every stage of medical care and in myriad ways. Within the section explaining current uses of 3D Printing in the medical industry, this thesis examines further possibilities for the technology. The only limit to implementation is how soon researchers discover new materials and methods. With the already widespread use and the vast resources universities and research teams are pouring into additive manufacturing, 3D Printing should be a ubiquitous technology in the medical industry within a few years.
As shown in the previous analyses, 3D Printing truly is a technology that could change the world. The barriers to adoption vary by industry, but a few general characteristics permeate across industries. If 3D Printing becomes faster and the material becomes cheaper, manufacturers could produce almost any product using the technology. Industries that involve mass customization, like the medical industry, already achieve the lowest cost per unit using 3D Printing. Future researchers could expand on this research by conducting detailed comparative statistical analysis or examine production per day limits, but those are outside of the scope of this thesis. Although 3D Printing is currently used for only a few final products, imminent technological and economic advances will lead to widespread adoption within the next decade.
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