Impact of 3D Printing on Global Supply Chains by 2020

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Abstract

This thesis aims to quantitatively estimate the potential impact of 3D Printing on global supply chains. Industrial adoption of 3D Printing has been increasing gradually from prototyping to manufacturing of low volume customized parts. The need for customized implants like tooth crowns, hearing aids, and orthopedic-replacement parts has made the Life Sciences industry an early adopter of 3D Printing. Demand for low volume spare parts of vintage cars and older models makes 3D Printing very useful in the Automotive industry. Using data collected from expert interviews, site visits, and online sources, and making assumptions where necessary, we developed our model by comparing the current supply chain processes and cost with the future supply chain processes and cost after 3D Printing was adopted. We also developed models to show future trends in 3D Printing adoption and costs. There were several challenges and limitations in this process due to limited availability of primary data, which led us to use secondary sources like the internet and make assumptions. One of the key features of our thesis is that we explicitly state all our assumptions, and present a model that is amenable to what-if analysis. Our analyses suggest that 3D Printing will change future supply chains significantly as production will move from make-to-stock in offshore/low-cost locations to make-on-demand closer to the final customer. This will significantly reduce transportation and inventory costs. The model shows that this will be especially true for low volume products. The models also show us the sensitivity analysis around the change in supply chain costs with the projected decrease in the cost and an increase in adoption of 3D Printing. The other major impact will be the reduction in lost sales due to unavailability of products and increase in customer satisfaction with almost 100% product availability. Finally, our analyses also indicate that 3D Printing could change the dynamics of the logistics industry: there may be reduction in the volume of freight business with an opportunity for 3PL companies to provide 3D Printing services in warehouses.

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On behalf of Varun Bhasin:
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1. Introduction and Motivation

This thesis aims at quantitatively estimating the potential future impact of 3D Printing on global supply chains. The advent of this disruptive technology (3D Printing) will change future supply chains considerably. Manufacturing will move from produce to order in factories to produce on demand at facilities near customers. There will be no need to transport a part from a far off location or to hold the part in a warehouse for a long time; rather it could be rolled off a 3D printer. This fact gives rise to an important research question: how will 3D Printing impact supply chains?

We begin with an overview of 3D Printing technology. Later we introduce our thesis sponsor, moving further into the practical motivation to research the topic.

1.1 What is 3D Printing?

3D Printing is also known as desktop fabrication or additive manufacturing, it is a prototyping process whereby a real object is created from a 3D design. The digital 3D-model is saved in STL format and then sent to a 3D printer. (3D Printing Basics, 2013) The term additive manufacturing refers to technologies that create objects through sequential layering. Many different materials can be used such as thermoplastics, polyamide (nylon), silver, titanium, steel, stereo lithography materials (epoxy resins), wax, photopolymers and polycarbonate. (3D Printing Basics, 2013) In 3D Printing, material is laid down layer by layer to create different shapes and objects such as tooth crowns, hearing aids, knee implants, automotive parts and many other items.

The concept of 3D Printing began to be taken seriously in the 1980s and has found increased application over the past few years. Led by Auto, Medical and Aerospace, 3D Printing to Grow into $8.4 Billion Market in 2025. (Lux Research, 2013) (Exhibit 1) The technology has the

potential to be a game-changer, transforming how manufacturing may be done in the future. 3D Printing offers a simple and fast design-to-create cycle for custom products that have to be manufactured in small quantities.

Another area where 3D Printing offers a huge advantage is on demand manufacturing of very slow moving high value products like automotive spare parts for vintage cars, spare parts for military equipment's in war zone etc. The application in design and manufacture of custom products has been found useful in fashion, home design and a number of other industries as well. (Hennessey, 2013) Recently, product designers are working on "Design for 3D Printing", which will provide corporations with a whole new way of designing, assembling and servicing products in the future. (Perez, 2014)

3D Printing will change the way manufacturing and distribution is done today. It will be disruptive to a number of old manufacturing technologies and will alter the supply chains of future.

1.2 Thesis Sponsor Introduction

Our thesis has been sponsored by DHL. Deutsche Post AG, operating under the trade name Deutsche Post DHL, is a provider of logistic solutions, with operations in more than 220 countries. The company primarily operates in Europe, the Americas, and Asia Pacific. It is headquartered in Bonn, Germany, and employed 428,287 people as of December 31, 2012. (Marketline, 2014)

DHL's supply chain division provides freight transportation, warehousing, distribution and value-added services to industry sectors including automotive, life sciences & healthcare, retail, technology, aerospace, chemical and energy. The value-added services offered to its clients

include sub-assembly and kitting for automotive, pre-warranty checks for technology products like laptops and mobile devices, packaging services, customization, postponement, and sequencing to pre-retail activities. Value added services is being seen as the key area of future growth by DHL leaders. By providing 3D Printing services to its client base DHL can expand its value added services offering.

DHL's Customer Solutions & Innovation organization focuses on the development and marketing of industry tailored solutions designed to simplify the lives of DHL customers. Solutions & Innovation performs research on tomorrow's logistics solutions, providing clients with the most advanced technology and services. DHL has been at the forefront of innovation having invested in R&D for services like 3D Printing, SmartScanner, RFID and Drone technology for parcel delivery. Our thesis to analyze "impact of 3D Printing on supply chains of future" is also an initiative by DHL in the same connection. It will help DHL to understand potential of 3D Printing technology in depth in regards to supply chains of future. It will also elaborate opportunities and threats posed to DHL because of this disruptive technology.

1.3 Practical motivation for 3D Printing

The industry adoption of 3D Printing is increasing at a rapid pace. According to a survey by *R&D Magazine* (Hock, 2014) to see what trends are important in the 3-D printing industry 47% of the respondents use 3-D printing as their additive manufacturing technique of choice, with stereo lithography (19%), fused deposition modeling (17%) and direct metal laser sintering (15%) as other common options. While 18% of the respondents already own a 3-D printer in their laboratory/organization, 39% are looking to purchase one; 43% say they aren't interested in purchasing a 3-D printer as it doesn't fit their research needs or their budgets.

The adoption of 3D Printing is providing a new way for companies to do manufacturing and impacting the logistics industry. Globally distributed manufacturing and supply chain networks can be considered the most influential megatrend affecting the logistics industry. Megatrends will shape the logistics sector as well as many other industries over the next few decades. (Terhoeven & Kückelhaus, 2013) This coupled with a demand for faster delivery of goods by customers and rising logistics costs is changing the way companies are looking at operating their supply chains in the future.

The other big customer trend has been an increasing demand for custom-designed products. (Sarah E. Needleman, 2010) Custom- designed shoes, mobile phone covers, and jewelry are gaining popularity.

Rapid advancement in technology is reducing product life cycles and making lead times shorter. For example, new models of iPhones are launched almost every year. This creates a volatile demand that requires short manufacturing to delivery time.

Logistics companies are trying to find ways to adapt to the future trends and align their service offerings with the demands of the market.

1.4 Research motivation

Supply Chain networks are becoming geographically complex. Even with the implementation of sophisticated technology and adoption of lean processes, organizations are facing the challenges of rising inventory levels and declining fill rates. Intense market competition and demand for faster lead times is putting a lot of pressure on supply chains.

3D Printing offers the capability to manufacture custom made products on demand in small batch sizes in physical proximity of the end customer. This postponement is a big advantage, offering flexibility in supply chains.

Our thesis provides a quantitative analysis comparing the supply chain costs of 3D Printing vs. traditional manufacturing.

Initially 3D Printing was mainly used in prototyping; however with advances in the technology both industries are seriously considering expanding 3D Printing capabilities to complement their traditional manufacturing.

The goal of our thesis is to quantitatively estimating the potential future impact of 3D Printing on global supply chains. We also aim to better understand how the adoption of 3D Printing will change total supply chain costs and impact key performance indices like manufacturing cost, transportation cost, inventory cost, and order fill rate.

2. Literature Review

There is literature available about the details of the 3D Printing process itself; however, the literature related to 3D Printing outlining its impact on supply chains is relatively scarce. Our literature review will cover an industry overview of 3D Printing. We will later look specifically at the Automotive and Life Sciences industries. Within these industries we have tried to study the existing supply chain processes and challenges. In the end we have tried to study how the adoption of 3D Printing can help alleviate some of these challenges.

2.1 3D Printing - Industry Overview

The earliest development of 3-D printing technologies happened at Massachusetts Institute of Technology (MIT) and at a company called 3D Systems. The earliest use of additive manufacturing was in rapid prototyping (RP) during the late 1980s and early 1990s. (Stephanie Crawford, 2011)

Industrial 3-D printing manufacturers have been offering their products for more than 20 years. Currently, more than thirty 3-D printing companies around the globe offer a range of industrial 3D Printing systems drawing on various technologies. More expensive systems produce fine-grained metal and polymer parts, while simpler systems use plastics. Today, some of the same 3-D printing technology that contributed to RP is now being used to create finished products. The technology continues to improve in various ways, from the fineness of detail a machine can print to the amount of time required to clean and finish the object when the printing is complete. The processes are getting faster, the materials and equipment are getting cheaper, and more materials are being used, including metals and ceramics. Printing machines now range from the size of a small car to the size of a microwave oven. (Stephanie Crawford, 2011)

In 2011, total industry revenues for industrial and professional purposes had grown to more than $1.7 billion, including both products and services. The industry's compound annual growth rate has been 26.4% over its 24-year history, and double-digit growth rates are expected to continue until at least 2019. (Lux Research, 2013)

While early systems were mainly sold to large, multinational customers, 3-D printing manufacturers more recently started to focus on the lower end of the market also, offering increasingly cheaper machines to make 3-D printing a viable option for small businesses, self-employed engineers and designers, schools and individual consumers (Ibid., p. 65 and 256).

According to Michael Fitzgerald (American writer for technical books) in Sloan Management Review, New Balance is doing customization for elite runners using a 3-D printing process. In January, a top middle-distance runner, Jack Bolas, raced in a New Balance shoe custom-made for his feet using a 3-D printing process. Similarly, Continuum, which calls itself the first collaborative fashion label, is using 3-D printing to allow for crowd-sourced fashion design, selling items in production runs of as few as one. It also sells a 3-D printed bikini ($250-$300) and jewelry. These examples show increased adoption of 3D Printing.

Today more than 30 companies are manufacturing 3D printers capable of manufacturing a wide variety of products with different quality standards using a number of materials like plastics, ceramics, and metals. 3D Systems and Stratasys are two big players in 3D printer manufacturing industry; their stocks have shown a 198% and 78% growth in one year from Dec 2012 to Dec 2013 respectively, making a good justification for positive outlook for 3D Printing.

2.2 Automotive industry

The automotive industry consists of cars and light trucks. The industry is fairly consolidated in few OEMs, however the automotive spare parts manufacturers are fairly fragmented across the globe. Adoption of 3D Printing in the automotive industry has been increasing slowly and gradually. (Lux Research, 2013) (Exhibit 1). 3D Printing has proved very useful in manufacturing low volume customized spare parts for vintage cars or specialized industrial vehicles.

2.2.1 Overview of Automotive Spare Parts

The motor vehicle aftermarket is a large sector of the U.S. economy employing nearly 4.1 million people in 2012. Sales in the automotive aftermarket (cars and light trucks) totaled $231.2 billion in 2012 representing a 3.5% increase over the previous year (APAA report).

According to a Deloitte report (2006), good after-sales service by a car manufacturer has become a critical success factor in sales of its new cars. At the same time, along with the increase in number of customer, the spare parts and service business is creating reliable revenues and considerable profits for automotive companies. Another study states that while 30% of dealers' revenues come from spare parts, 50% of the profits come from spare parts. This makes spare parts a critically important line of business for car dealers. (Bijl, Mordret, Multrier, Nieuwhuys, & Pitot, 2000)

Thomas S. Spengler from the Department of Production Management, Braunschweig University of Technology, created a chart to show the life cycle in the automotive Industry. According to his study, a typical car model is in production for seven years followed by a fifteen year

maintenance period. (Exhibit 3) Producers have to assure spare parts supply for the average lifetime of the product.

A new study by the auto research firm Polk finds the average age for vehicles in America has climbed to an all-time high of 11.4 years. Globally vehicles aged over 6 years (the critical age at which after-sales demand is triggered) is increasing. (Exhibit 4) As the age of vehicles increases, the role of Original Equipment Manufacturer (OEM) service and spares becomes more important.

2.2.2 Challenges in the current Supply Chain of automotive spare parts

The unique attributes of parts business generate its complexity. The life cycle of spare parts is longer than that of vehicles, and the total number of SKUs is large. Additionally, the demand for parts is relatively unstable and difficult to forecast. These circumstances pose enormous challenges to parts planning, purchasing, ordering, and logistics, among other operations. According to a Deloitte report, most managers in the spare parts business area believe that the major barriers lie in planning stable supply of parts, supplier collaboration, information systems, data management, and supply chain visibility. (Driving Aftermarket Value: Upgrade Spare Parts Supply Chain, 2011)

According to a case study, (Botter & Fortuin, 2003) service part inventories cannot be managed by standard inventory control methods, as conditions for applying the underlying models are not satisfied because of challenges stemming from the huge number of parts SKUs, unstable and unpredictable demand, as well as the complexity of the overall supply and distribution network. Nevertheless, the basic questions have to be answered: Which parts should be stocked? Where

should they be stocked? How many of them should be stocked? Table 1 below depicts KPIs benchmark for spare parts management.

Table 1: Spare Parts Management KPIs Benchmark

	World Average*	World Best*
Facing Fill Rate#	95%	97%
Annual Inventory Turns	3.6 Turns	4.6 Turns
Order to Delivery Lead Time	≤24 hours: 17.5%	≤8 hours: 1% ≤24hours: 47.5%
Logistics Cost as a % of Sales$^{\beta}$	8.8%	5.8%

* World average and world best data were referenced from Deloitte Global Service and Parts Management Benchmark Survey

Facing Fill Rate is the percentage of order lines which can be filled by facing warehouse. There are different definitions and calculation formulas for this KPI among the OEMs involved in this survey

β Only outbound transportation cost and warehouse management cost are included in logistics cost, which is impacted by logistics operation model of most Chinese OEMs

Source: Deloitte Global Service and Parts Management Benchmark Survey (year)

2.2.3 3D Printing in the Automobile industry

The complexity of the automobile spare parts business makes it an excellent candidate for 3D Printing. The existing supply chains can be simplified if the majority of the spare parts can be 3D printed on demand. This will reduce the lead time and inventory storage cost, and is expected to improve customer satisfaction by ensuring near 100% availability.

An industry report by Javelin Tech (2009) suggests that replacing expensive and lead-time critical Computer Numerically Controlled (CNC) milled parts with in-house manufactured parts using 3D Printing can reduce production costs for companies. The printed parts also perform the same, weigh less, and are well suited for the production of complex bodies that, when using conventional metal-cutting processes, would be very difficult and costly to produce. This reduces lead time, inventory storage and transportation cost, and improves availability (Javelin Tech, 2009)

Jay Leno, who is a famous comedian and late night show host, is a vehicle enthusiast as well. Leno owns approximately 886 vehicles (769 automobiles and 117 motorcycles) (Jay Leno's Garage, 2014) He writes, "One of the hardships of owning an old car is rebuilding rare parts when there are simply no replacements available. My 1907 White Steamer has a feed water heater, a part that bolts onto the cylinders. It's made of aluminum, and over the 100-plus years it's been in use. So, rather than have a machinist try to copy the heater and then build it, we decided to redesign the original using a 3D scanner and 3D printer. These incredible devices allow you to make the form you need to create almost any part." Jay Leno uses 3D Printing extensively in his garage to restore and repair vintage cars and motorcycles.

The above cases are illustrative examples of how 3D Printing is being adopted for making customized low volume automotive spare parts.

2.3 Life Sciences industry

Life Sciences is another industry that is in great need of highly customized and low volume products. Most of these products are implants are surgical instruments that are made to order for a particular patient.

2.3.1 Overview of Life Sciences industry (Medical Implants and Surgical Devices)

Medical implants are artificial devices that are used to replace damaged or missing biological structures. The global revenue generated by medical device manufacturing companies is over $200 billion, with more than $85 billion of that being generated by U.S. based medical device companies (Medical Implants Market - Growth, Global Share, Industry Overview, Analysis, Trends Opportunities and Forecast 2012 - 2020, 2014). The medical implants market is driven by an increase in the health needs of elderly people, and advancement in medical technologies. Increase in demand for the reconstruction of joints and replacement structures for ophthalmic

and dental needs is expecting growth in medical implant market (Medical Implants Market - Growth, Global Share, Industry Overview, Analysis, Trends Opportunities and Forecast 2012 - 2020, 2014)

According to a 2014 report from Allied Market Research, the global surgical device market which includes surgical implants and surgical instruments, including cardiovascular devices, was valued at $240 billion in 2013. The increase in incidence of heart related problems is due mainly to changes in lifestyle. These lifestyle changes have increased the rate of heart surgeries. The U.S. is the leading market for cardiovascular surgical devices due to an increase in the aging population.

The growth of the surgical device market is also due to advances in anesthetics, emerging economies, and technological innovation. GBI Research predicts that the global surgical equipment market will surpass $7 billion by 2016, with a 6% compound annual growth rate (Surgical Equipment Industry: Market Research Reports, Statistics and Analysis, 2014).

According to Administration on Aging Statistics Report, the older population in the U.S. (persons 65 years or older) numbered 40 million in 2009. They represented 13% of the population, or about one in every eight Americans. By 2030, there are projected to be about 72 million older persons, more than twice the number in 2000. People 65+ are expected to grow to be 19% of the population by 2030 (Aging Statistics, 2014).

According to a Deloitte report, the medical technology market (including medical implants and surgical devices segments) is expected to grow at a rate of 4.5 percent per year between 2012 and 2018, reaching global sales of $455 billion (Deloitte Global Life Sciences Outlook, 2014).

2.3.2 Challenges in the current Supply Chain of the Life Sciences

The supply chain for implantable devices from the point of manufacture to the point of use is complex because of the complex nature of interactions between the hospitals, company sales executives and warehouses. (The Current State of the Implantable Device Supply Chain, 2012). According to a 2012 report by GHX on current state of implantable device supply chain, the ineffective management of implantable medical devices (e.g., hips, knees, and cardiac stents) affects healthcare efficiency and profitability for both healthcare providers and suppliers. While implants in the U.S. represent approximately $40 billion as a market segment, lack of visibility and control over these devices costs the healthcare industry an estimated $5 billion per year from inefficient, disconnected manual processes, and lost, expired and wasted product.

Implantable devices are expensive, can account for up to 80 percent of the total cost of a procedure, and are difficult to track. They are often delivered by a supplier sales rep or stored within a hospital and processed as consigned, bill-only orders once they are used. In a typical implant procedure scenario, circulating nurse and the suppliers sales rep use stickers from the implant packaging to log usage on separate paper records of what was used in the operating room (OR). Implant stickers are often left stuck to the work surface of the nurse's workstation when demands in the OR require attention. When nurses return, they pick up where they left off. Moreover, doctors want to hold different sizes of implants to guard against any uncertainty arising during operation in regards to matching the exact size of implant to the patient's needs. So, a big challenge is highly manual, disjointed and duplicative processes surrounding the use of implantable devices in the operating room and catheterization laboratory. The end result is that without visibility of, and accurate accounting for, inventory, products are lost, billed for improperly, and frequently expire before they can be used, with little documentation of product-

to-patient information in the event of a recall. (The Current State of the Implantable Device Supply Chain, 2012)

An expectation in the health care industry is that there should be no stock out because the implantable device required in the operating room for the patient under surgery may be the only thing between life and death. Overall, this expectation gives rise to large inventories without visibility and tracking. There is a huge improvement opportunity in the implantable devices supply chain.

2.3.3 3D Printing in the Life Sciences industry

3D Printing has great potential to be an industry game changer in the Life Sciences supply chains because customized medical implants and devices can be made to exactly match the need of the person who requires it. The 3D implants include tooth crowns, hearing aids, coronary implant materials, and orthopedics replacements like knee and hip implants. In the orthopedics sector, adoption of 3D Printing is growing at a fast pace.

Health care facilities hold large inventories because Life Sciences parts require a very high service level. For example, for a knee replacement surgery, the doctor may hold about 6 to 12 different sizes and types of knee implants in order to cover for uncertainties faced during surgery (Expert on Life Sciences Supply Chain, 2014). This huge inventory and its related costs can be drastically reduced by 3D Printing, which enables production of an exact size of knee implant based on the patients' MRI images leaving no room for ambiguity. In this way, no hit and trial for finding exact size is required.

In the past few years, 3D Printing has been used to make prosthetic limbs for those who lost their arms or legs. According to a recent article published at 3ders.org, a man named Jose Delgado Jr.

was using a traditionally manufactured prosthetic hand that cost him $42,000. Jeremy Simon of 3D Universe, a company that makes 3D Printing prosthetics, could make a 3D printed hand for him in $50 using the design made by an assistant professor of Creighton University. Jose has been using multiple types of prosthetic devices for years and he said that he prefers the 3D printed hand to his far more expensive myoelectric prosthetic hand. (Comparing: $50 3D printed hand vs. $42,000 prosthetic limb, 2014)

In intricate heart related surgeries, doctors make a 3D replica of the heart before the surgery so that they can have an exact idea about the shape and minute details and they can plan better for the surgery. (U of L physicians create 3D heart replica for toddler's life-saving surgery, 2014)

An advanced type of 3D Printing used in Life Sciences industry is called biological 3D Printing or "bioprinting". Bioprinting is the construction of a biological structure by computer-aided, automatic, layer-by-layer deposition, transfer, and patterning of small amounts of biological material (Printing Body Parts - A Sampling of Progress in Biological 3D Printing, 2014). One goal of bioprinting is to be able to print biological tissues for regenerative medicine. For example, in the future, doctors may repair the damage caused by a heart attack by replacing the damaged tissue with tissue that has rolled off of a printer. Researchers have already implanted some 3D-printer generated structures in human patients. Several bone replacement projects have been reported. In June 2012, surgeons in Belgium implanted a jawbone replacement in a woman suffering from oral cancer and infection. Cornell University researchers have fabricated a 3D printed replacement external ear as shown in figure 1 below.

Lawrence Bonassar, associate professor of biomedical engineering, and colleagues collaborated with Weill Cornell Medical College physicians to create an artificial ear using 3D Printing and injectable molds. Lindsay France/University Photography

Figure 1: 3D Printing in Life Sciences

The above mentioned industry examples present a strong support in favor of industry adoption of 3D Printing in the Automotive and Life Sciences industry.

3. Research Methods

To analyze the impact of 3D Printing on supply chains in the Automotive and Life Sciences industries, we first built models of total supply chain cost for manufacturing using traditional and 3D Printing. We then estimated cost parameters to perform a quantitative assessment of the current total supply chain costs in those industries with the total costs that would be incurred if those supply chains used 3D Printing.

To assess the current supply chains, we collected data by interviewing industry experts and conducting site visits. To determine what cost elements to address, we used the total supply chain cost model by (Silver, Pyke, & Peterson, 1998). Based on the information gathered in our interviews, we developed a mathematical model to analyze how 3D Printing will change supply chain costs in the future.

In the following paragraphs, we describe the steps taken in gathering and analyzing data in order to develop our model for total supply chain costs.

3.1 Data Collection

Data collection was carried out through site visits, face-to-face interviews, phone conferences and secondary research.

3.1.1 Site Visits

In order to understand current supply chain processes, we visited a distribution center in the automotive industry and another in the Life Sciences industry. We wanted to understand the DCs' inbound and outbound operations, including product supply and demand, the total inventory value at the distribution center, and how the products were being shipped from suppliers to the DC and from the DC to customers. During the visit we observed multiple steps

that the products went through, from the receipt of shipments from suppliers to the storage of the products in the DC to the shipment of the products to customers. The warehouse personnel explained each step along the way and provided insights into the logic behind each activity. They used characteristics of products to improve their warehouse management operations for example heavy and bulky products were usually stored in lower racks for ease of handling and from where these products could be easily picked up by fork lifts. There were different sections for different categories of products, including "fast movers", "slow movers" and "very slow movers". These were the products that had a shelf life of approximately 2 weeks, 12 weeks, and 26 weeks respectively.

The purpose of these visits was to accurately develop the process map of the current supply chain and to become familiar with the different parties involved in the process. Observing the inbound and outbound operations of these DCs provided a detailed perspective for understanding all supply chain cost elements. At the end of each site visit, we met with the parties involved to discuss ideas regarding how 3D Printing may change the future supply chains. Such meetings reemphasized the value of open communication among all parties in improving the overall operation of the supply chain.

We also visited two 3D Printing companies to study this technology in detail. We observed multiple steps required for 3D Printing of a part. These include producing 3D model of part, transfer of file to computer that controls 3D printer, machine setup, layer by layer build-up, removal of part from 3D printer and post processing including chemical bath and cleaning. We also discussed how these firms experienced increase in demand of 3D Printing over last couple years.

3.1.2 Face-to-Face/Telephone Interviews and Interview Protocol

We interviewed automotive and Life Sciences experts either in person or by telephone. (Exhibit 5) Both face-to-face and telephone interviews were very helpful for providing industry insights in the data collection phase. Interview respondents were of manager or director level seniority and we met with them or talked to them for one to one and a half hours. All respondents requested anonymity, but agreed to let us reference their comments.

During each of these calls, the respondent explained the current supply chain processes used for flow of products in his/her particular industry. In addition, the respondent talked about his/her perspective of 3D Printing. Following the explanations, we questioned the respondents to get further insights by using the interview protocols mentioned below. These interviews were instrumental in developing a complete understanding of the current supply chain system. Table 2 below shows interview protocol for automotive expert.

Table 2: Interview Protocol for Automotive Expert

Interview Protocol for Automotive Expert
Describe the detailed process for
- Spare parts procurement
- Spare parts distribution to dealers
# of Car Models
# of Years for which Spare Parts are maintained
Average # of SKU`s per model in inventory
Total # of SKU`s in store
Spare Parts Categorization
Lead Time for new spares (0-5Yrs)
Lead Time for medium spares (6-10Yrs)
Lead Time for old spares (11-20Yrs)
$ Value of total inventory in store
Inventory Turn over
Stock Out %
Weekly inbound volume
Weekly outbound volume
Order Fill Rate
Shipping Cost
Holding Cost
Ordering cost
Cost of lost sale
What are the industry pain points

Interview protocol for Life Sciences expert is depicted in Table 3 below. The interview helped us understand the existing supply chains processes and get quantitative data around the below parameters.

Table 3: Interview Protocol for Life Sciences Expert

Interview Protocol for Life Sciences Expert
Describe the detailed process for
- Surgical Instruments & Implants procurement
- Surgical Instruments & Implants distribution to Hospitals
# of Instrument Types
Total # of SKU`s in warehouse
Spare Parts Categorization
Lead Time for fast movers, slow movers, very slow movers
$ Value of total inventory in store
Inventory Turn over
Stock Out %
Weekly inbound volume
Weekly outbound volume
Order Fill Rate
Shipping Cost
Holding Cost
Ordering cost
Cost of lost sale
What are the industry pain points

3.1.3 Secondary Research (Internet)

Availability of data to develop a quantitative model to estimate the potential future impact of 3D Printing on global supply chains from primary sources was limited and thus required us to use secondary sources like internet. We took quotes from a number of websites to calculate transportation costs for ocean and ground shipping including *chinashippingna.com, alibaba.com,* and *data.worldbank.org.*

We also researched 3D Printing applications, types of 3D Printing materials being used, future trends and costs from journals and web articles. Quotes from a number of websites were taken to

compare 3D Printing cost and check the availability of different materials. For complete list of sources, see Exhibit 6

We searched for use cases where 3D Printing is currently being used to analyze its manufacturing cost advantage against traditional manufacturing.

Data from secondary sources provided useful insights and was helpful in filling the gaps where data from primary sources was not available.

3.2 Study of Total Supply Chain Costs

By conducting site visits and interviews with the industry experts, we got an idea about the current supply chain for an Automotive/Life Sciences part. We have depicted it in Figure 2 below.

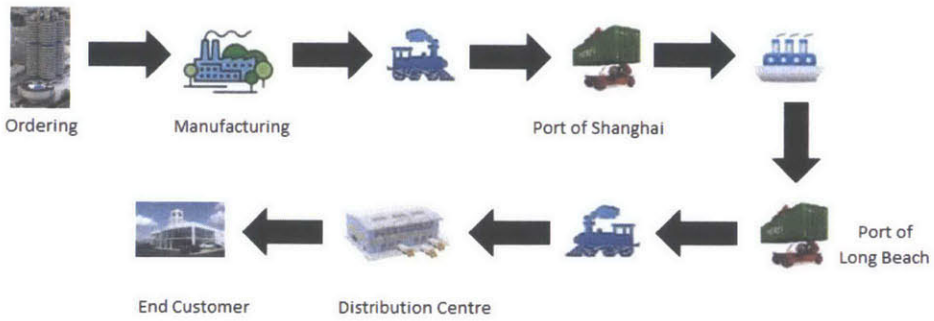


Figure 2: Current Supply Chain for an Automotive/Life Sciences Part

The main aim of our project was to compare current total supply chain costs and total supply chain costs with 3D Printing. We compared costs in six fundamental categories:

a. Purchase or manufacturing cost

b. Ordering cost

c. Transportation cost

d. Inventory holding cost

e. Pipeline inventory cost

f. Stock-out cost

The total supply chain costs are expressed as follows:

$$Total\ Cost = Purchase\ or\ manufacturing\ Cost + Order\ Cost + Transportation\ Cost + Inventory\ Holding\ Cost + Pipeline\ Inventory\ Cost + Stock\ Out\ Cost \quad (1)$$

3.2.1 Purchase/Manufacturing Cost

An item can either be purchased or manufactured in house. Purchase/Manufacturing cost is the amount a company pays for purchasing an item or manufacturing it. In either case, its cost will be calculated as follows:

$$\text{Purchase or ManufacturingCost (\$/time)} = vD \quad (2)$$

where

D = Average Demand $(\frac{\text{units}}{\text{time}})$, D is the average demand of the item in terms of units/time.

v = Purchase or Manufacturing Cost $(\frac{\$}{unit})$

The unit value, or unit variable cost (denoted by symbol v), of an item is expressed in dollars per unit. If it is purchased, this is the price paid to the supplier. If it is manufactured in house, the unit value of an item is more difficult to determine. However it can be calculated using this simple approach:

$$v_m = \text{Manufacturing Cost}\left(\frac{\$}{\text{unit}}\right) = F + b\,(D) \quad (3)$$

where

F = Fixed Cost of the Manufacturing Capability ($)

b = Variable Cost for Manufacturing $\left(\frac{\$}{unit}\right)$

For the model under study, $v = v_m$

3.2.2 Ordering or Setup Cost

Ordering or setup cost includes the cost of order forms, postage, telephone calls, authorization, typing of orders, receiving orders, inspection, following up on unexpected situations, and handling of vendor invoices.

$$\text{Order Costs } \left(\frac{\$}{\text{time}}\right) = A\left(\frac{D}{Q}\right) \qquad (4)$$

where

A = Fixed Ordering or Transaction Cost $\left(\frac{\$}{\text{order}}\right)$

The symbol A denotes the fixed cost (independent of the size of the replenishment) associated with a replenishment.

Q = Replenishment Order Quantity $\left(\frac{\text{units}}{\text{order}}\right)$

T = Order Cycle Time $\left(\frac{\text{time}}{\text{order}}\right)$

3.2.3 Transportation Cost

Transportation cost is the cost associated in transporting an item. Many products in today's global supply chains are manufactured in Asia, so in a typical scenario, the item is shipped from its manufacturer's location to the Asian port, from where it will be transported through ship to the US port; thereon it will be carried by a truck to the distribution center.

$$\text{Transportation Cost } \left(\frac{\$}{\text{time}}\right) = D\ (c_1 m_1 + c_2 m_2 + c_3 m_3) \qquad (5)$$

where

c_1 = Cost of transportation from Manufacturer to Asian Port $\left(\frac{\$}{\text{mile}}\right)$

c_2 = Cost of transportation from Asian Port to US Port $\left(\frac{\$}{\text{mile}}\right)$

c_3 = Cost of transportation from US Port to DC $\left(\frac{\$}{\text{mile}}\right)$

m_1 = Miles from Manufacturer to Asian Port

m_2 = Miles from Asian Port to US Port

m_3 = Miles from US Port to DC

3.2.4 Inventory Holding Cost

The cost of holding or carrying items in inventory includes the opportunity cost of the money invested, the expenses incurred in running a warehouse, handling and counting costs, the costs of special storage requirements, deterioration of stock, damage, theft, obsolescence, insurance, and taxes. The largest portion of holding cost is made up of the opportunity cost of the capital tied up

that otherwise could be used elsewhere in an organization and the opportunity cost of warehouse space claimed by inventories. (Silver, Pyke, & Peterson, 1998)

Figure 3 below shows the components of Inventory Holding Cost (Johnson & Wood, 1986)

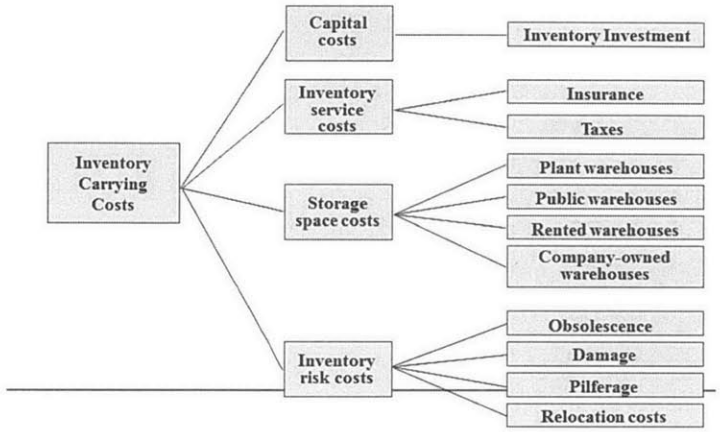


Figure 3: Components of Inventory Carrying Cost

$$\text{Inventory Holding Cost} = v\,r\,\left(\frac{Q}{2} + k\,\sigma_L\right) \qquad (6)$$

where

$r = \text{Carrying or Holding Charge}\ \left(\dfrac{\$}{unit\ time}\right)$

$L = \text{Lead Time (time)}$

Replenishment lead time, L is the time that elapses from the moment at which it is decided to place an order, until the item is physically on the shelf ready to satisfy customer demands.

$I = \text{Inventory On Hand Average (units)} = \dfrac{\text{Q}}{2}$

k = Safety factor based on service level

σ_L = Standard Deviation of Demand over Lead Time

3.2.5 Pipeline Inventory Cost

Pipeline inventory cost is the holding cost incurred for goods in transit (for example, in physical pipelines, on trucks, in air or in railway cars) between levels of a multi-echelon distribution system. Pipeline inventory can be calculated by multiplying demand and lead time. The higher the lead time, the greater the pipeline inventory will be.

$$\text{Pipeline Inventory Cost} = v\, r\, (DL) \qquad (7)$$

where

Demand over Lead Time = $D\ L$

3.2.6 Stock-Out Cost

This cost is incurred when stock-outs take place, this includes lost profits, potential lost profits due to sales of complimentary goods, potential loss of customer etc. In the case of a manufacturer, it includes the expenses that result from changing over equipment to run emergency orders and the attendant costs of expediting, rescheduling, split lots and so forth. For a customer, it includes emergency shipments or substitution of a less profitable item. This cost results from not servicing the customer demand. It includes the goodwill lost as a result of poor service (Silver, Pyke, & Peterson, 1998). The customer may or may not be willing to wait while the item is backordered. The customer may not ever return, and he may tell his colleagues about the disservice. All these concepts are associated with stock-out cost, which is why it is important to calculate this cost element.

$$\text{Stock Out Cost} = B_2 \left(\frac{D}{Q}\right) P_u \geq (k) \qquad (8)$$

where

B_2 = Penalty for shortage beyond lost profit (% of item cost, it is not $ value)

Q = Replenishment Order Quantity $\left(\frac{\text{units}}{\text{order}}\right)$

$P_u \geq (k)$ = Probability of a stock out per cycle

$If \frac{Qr}{DB_2} \leq 1 \; then \; P_u \geq (k) = \frac{Qr}{DB_2}$ otherwise set k as low as management allows

3.2.7 Total Cost

The total cost expression in terms of dollars per time for one SKU in the current supply chain will be expressed as following: Total Cost $\left(\frac{\$}{\text{time}}\right) = TC$

$$Total\ Cost = Purchase\ or\ manufacturing\ Cost + Order\ Cost + Transportation\ Cost + Inventory\ Holding\ Cost + Pipeline\ Inventory\ Cost + Stock\ Out\ Cost \qquad (1)$$

$$TC = v\,D + A\left(\frac{D}{Q}\right) + D\,(c_1 m_1 + c_2 m_2 + c_3 m_3) + v\,r\left(\frac{Q}{2} + k\,\sigma_L\right) + v\,r\,(DL) + B_2\left(\frac{D}{Q}\right) P_u \geq (k) \qquad (1)$$

3.3 Study of 3D Printing Cost

The cost of 3D Printing is defined as the cost to manufacture a given product using additive manufacturing, or 3D Printing. In this section we will be comparing the cost of manufacturing a product via 3D Printing and traditional manufacturing methods like injection molding.

The initial capital investment required for 3D Printing is the cost of the printer and its setup. Variable cost includes the one-time product design cost, material cost and miscellaneous cost like electricity, personnel etc. Once the product design is ready, it can be sent to a 3D printer, which will manufacture the part using the specified material.

$$Total\ Installation\ Cost,\ I_{3D} = C_P + C_{SD} \qquad (9)$$

where

I_{3D} = Intial Setup Cost for 3D Printing ($)

C_P = Cost of 3D Printer ($)

C_{SD} = Other Setup Costs for 3D Printing ($)

$$\text{Total Manufacturing Cost using 3D Printing, } M_{3D}\ (\tfrac{\$}{EA})$$

$$\text{Total Manufacturing Cost using 3D Printing, } M_{3D} = \frac{C_D}{q} + C_{MD} + C_{OD} \qquad (10)$$

where

C_D = Cost of Designing a Part ($)

q = Quantity Manufactured (EA)

C_{MD} = Cost of Material for 3D Printing ($)

C_{OD} = Other Manufacturing Cost for 3D Printing ($)

Now we compare the costs associated with manufacturing the same product using an injection molding technique. The initial capital investment required for injection molding is the cost of an

injection molding machine and setup cost. The variable cost will include a onetime product design cost and the cost of mold. Material cost and miscellaneous cost like electricity and personnel are the other main variable costs. Once the product design and mold are ready, manufacturing can be done in large lot sizes using the injection mold machine and the specified material.

$$I_{IM} = C_I + C_{SI} \qquad (11)$$

where

I_{IM} = Intial Installation Cost for Injection Molding ($)

C_I = Cost of Injection Molding Machine ($)

C_{SI} = Other Setup Costs ($)

$$Total\ Manufacturing\ Cost\ using\ Injection\ Molding = M_{IM}(\frac{\$}{EA})$$

$$M_{IM} = \frac{C_D}{q} + \frac{C_{MM}}{q} + C_{MI} + C_{OI} \quad (12)$$

where

C_D = Cost of Designing a Part ($)

C_{MM} = Cost of Injection Mold ($)

C_{MI} = Cost of Material for Injection Molding ($)

q = Quantity Manufactured (EA)

C_{OI} = Other Manufacturing Cost for Injection Molding ($)

3.3.1 Future Projection of 3D Printing Cost

The future costs for 3D Printing will depend on the growth and adoption of 3D Printing technology. The two costs that will have a significant impact on the total manufacturing cost for 3D Printing will be the cost of the 3D printer and the cost of material. Currently, 3D printers are being manufactured on a very small scale; adoption of 3D Printing and growth in its application will lead to a higher demand for 3D printers, bringing economies of scale.

Most of the 3D printer manufacturers today have patent protected the materials that can be used on their 3D printers. This is a monopoly situation where a customer is forced to buy material from the 3D Printing manufacturer. As the demand for 3D Printing grows and a number of new materials are developed to be used for 3D Printing, it is envisioned that other companies for 3D Printing material will come into the market, thereby reducing the cost of material, similar to printer cartridges.

Gartner's Hype Cycle Special Report provides strategists and planners with an assessment of the maturity, business benefit and future direction of more than 2,000 technologies, grouped into 98 areas. Figure 4 below shows the Gartner Hype Cycle for Emerging Technologies. (Gartner Hype Cycle for Emerging Technologies, 2012). 3D Printing has been steadily climbing to the peak of 'Inflated Expectations' over the past few years. It is interesting to compare the Hype cycle for 2012 and 2013. In 2012, 3D Printing sits on top poised for the drop into the 'Trough of Disillusionment'. It is also interesting to note that in 2013, as shown in Figure 5, 3D Printing has been split into Consumer 3D Printing and Enterprise 3D Printing. While the Consumer 3D Printing is still sitting on the peak of 'Inflated Expectations', Enterprise 3D Printing is evolving rapidly and is on the 'Slope of enlightenment' and is expected to reach the 'plateau of productivity' in next 2-5 years.

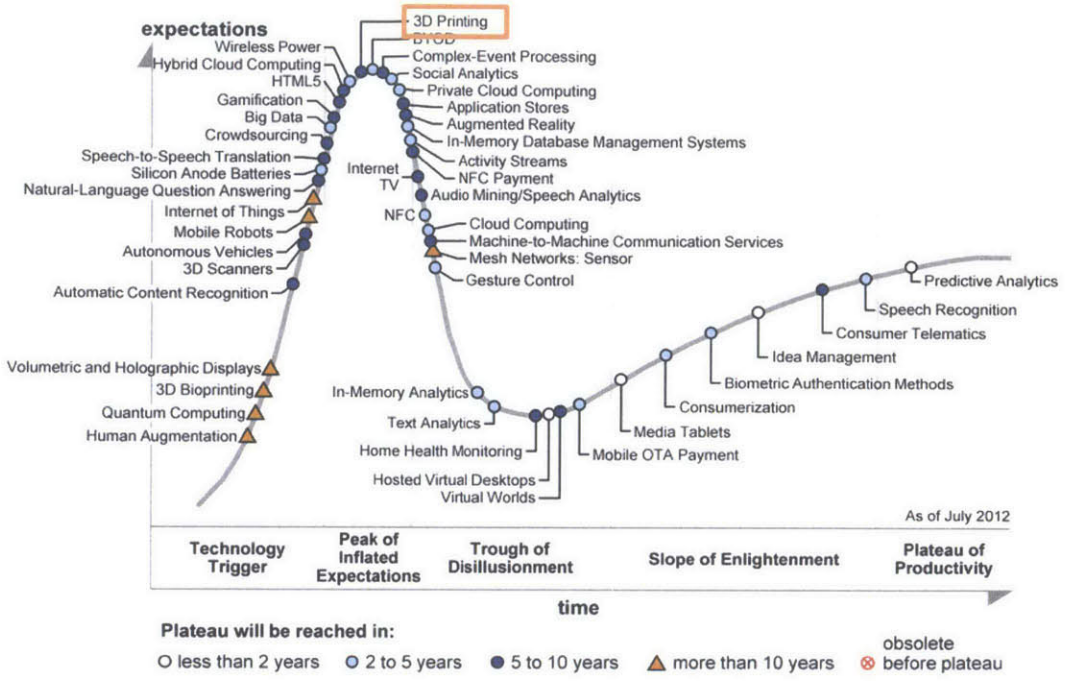


Figure 4: Gartner Hype Cycle for Emerging Technologies 2012

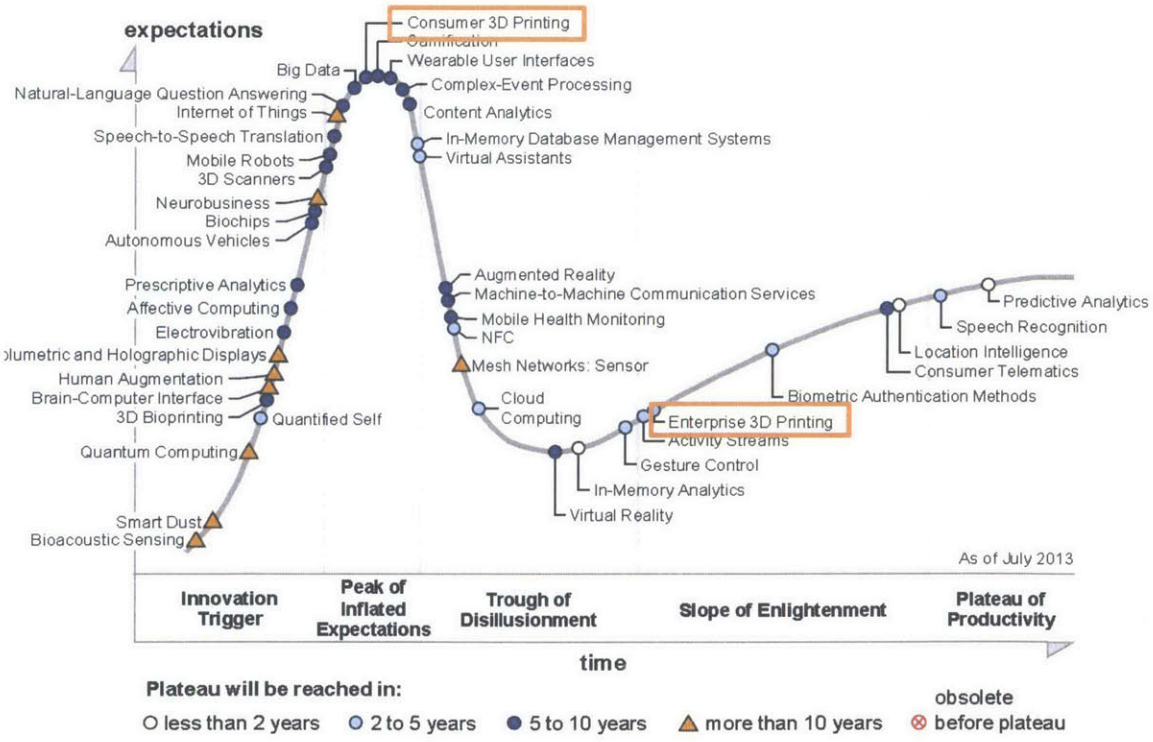


Figure 5: Gartner Hype Cycle for Emerging Technologies 2013

Although we agree that 3D Printing is not yet being used by everyone around the world, but its awareness and use is growing incredibly fast, and industry experts expect that it will reach the 'Plateau of Productivity' within 5-10 years (Gartner Hype Cycle for Emerging Technologies, 2013)

Once the 'Plateau of Productivity' is reached the growth is expected to follow a typical 'S' Shaped curve as shown in Figure 6 below. The 'S' Shape curve shows the adoption of new technologies in the marketplace and corresponding increase in market share. (Diffusion of innovations, 2014)

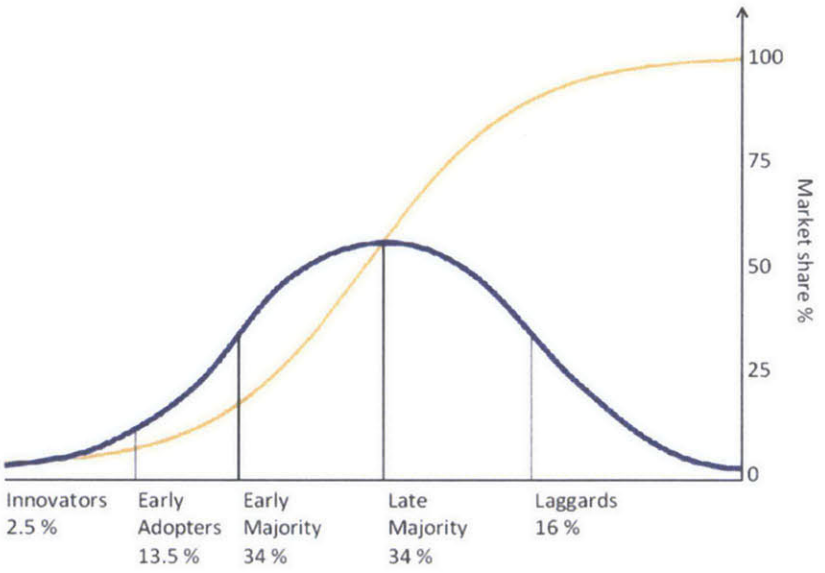


Figure 6: S-Shaped Curve for Adoption of Technology

The cost of 3D printers has decreased in the years from 2010 to 2013, with machines generally ranging in price from $20,000 just three years ago, to less than $1,000 in the current market. Some printers are even being developed for under $500, making the technology increasingly available to the average consumer. (The History of 3D Printing, 2014)

4. Results

In this chapter, we demonstrate the results of our model and the interpretation of these results. We discuss three cases. The first case is the comparison of total supply chain costs for a warehouse before and after the use of 3D Printing. The second case explains comparison of these costs for an automotive item, and the third case focuses on a cost comparison of a Life Sciences item.

4.1 Cost of 3D Printing

Before moving on to the three cases, we compared the cost of 3D Printing and traditional manufacturing.

4.1.1 Cost of 3D Printing vs. Traditional Manufacturing

To draw this comparison, we took a simple product, an iPhone case, which is currently being produced by 3D Printing as well as traditional manufacturing. We will use this as an illustration to show the comparison in manufacturing costs using the two techniques.

In computing the cost we did not take into account the initial setup cost. Both 3D Printing and traditional manufacturing using injection molding require a one-time design cost, which is similar for both the technologies (3D Printing Expert, 2014). Injection molding has a higher setup cost, which is mainly associated with the cost of the mold needed to shape the product. 3D Printing does not have any other set-up costs; once the design is ready it can be sent to the 3D printer for manufacturing.

For manufacturing using 3D Printing we took a price quote from a number of famous 3D Printing companies. These price quotes are presented in Table 4 below.

Table 4: Price of 3D Printing

Company	Price 3D Print
makexyz.com	$6.50
Sculpteo	$11.35
3dprintuk	$15.49
Shapeways	$15.68
Panashape.com	$16.71
Average 3D Printing	**$13.15**

For traditional manufacturing using injection molding, we took a price quote from two wholesalers from China. The price quotes are presented in Table 5 below.

Table 5: Price of Traditional Manufacturing (Injection Molding)

Company	Price Injection Molding
Dhgate	$0.60
Alibaba	$0.89
Average Injection Molding	**$0.75**

The comparison between 3D Printing and injection molding is depicted in Table 6 below.

Table 6: Price Comparison between 3D Printing and Traditional Manufacturing

Cost Variable	3D Printing	Injection Molding
C_D	$3,000	$3,000
C_{MM}		$8,500
$C_{MD} + C_{OD}$	$13.15	$0.75

*Values of cost of designing a part (C_D), cost of injection mold (C_{MM}) have been assumed based on discussion with 3D Printing experts

Next we used the price equations developed in Section 3.3 to determine the unit cost of manufacturing using the two technologies for the given quantities. Table 7 below shows the cost comparison of manufacturing the sample product by 3D Printing versus injection molding.

Table 7: Cost per Unit Comparison between 3D Printing and Traditional Manufacturing

Quantity (q)	Cost Per Unit		% Difference
	3D Printing(M_{3D})	Injection Molding(M_{IM})	
10	$313.15	$1,150.75	-267%
100	$43.15	$115.75	-168%
250	$25.15	$46.75	-86%
500	$19.15	$23.75	-24%
750	$17.15	$16.08	6%
1000	$16.15	$12.25	24%
2000	$14.65	$6.50	56%
4000	$13.90	$3.63	74%
6000	$13.65	$2.67	80%
8000	$13.53	$2.19	84%

For a small quantity, the cost of 3D Printing is much more economical; however as we get into larger quantities, the economies of scale in injection molding far exceed the initial advantage of 3D Printing. The cost of 3D Printing raw material (resin) is also much higher than the cost of plastic used in injection molding due to manufacturer patents as discussed earlier, in Section 3.3.1. Figure 7 below shows this comparison between 3D Printing and injection molding.

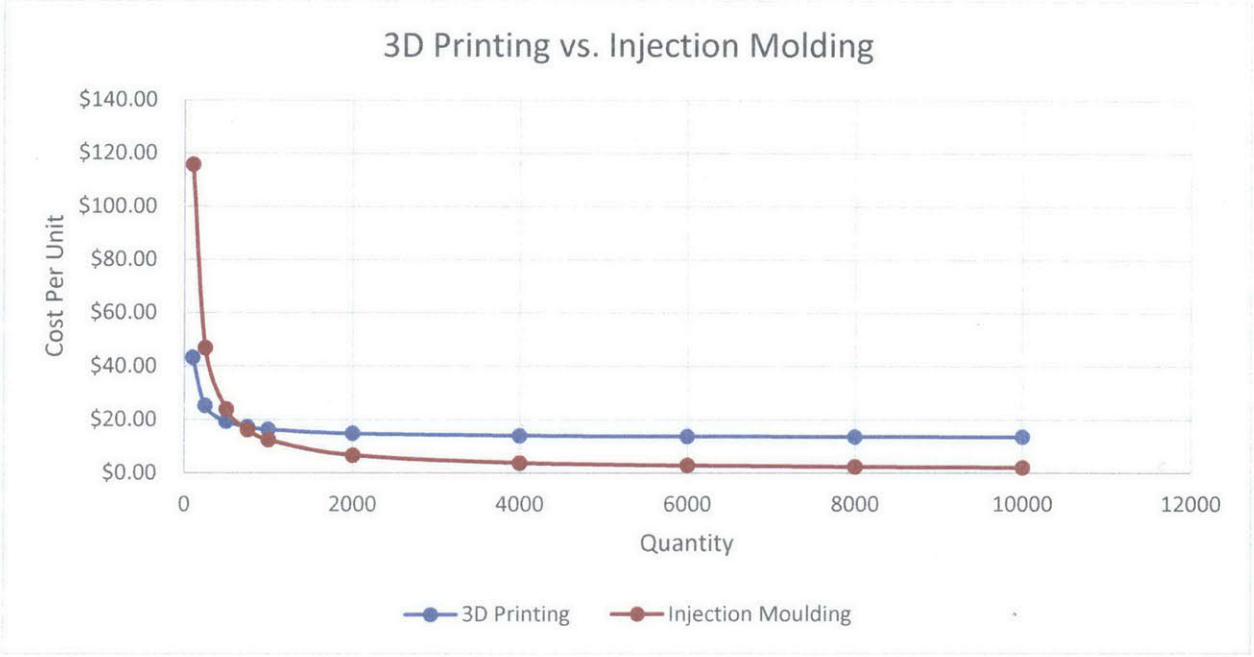


Figure 7: Comparison between 3D Printing and Injection Molding Cost

4.1.2 Future Cost of 3D Printing

In this section we attempt to quantify the potential cost reduction. The cost of 3D printer and 3D Printing material are the two main costs associated with 3D Printing.

We studied the growth in adoption and its effect on price for a number of technology products including RFID, LED, television and robotics. Based on our research, we hypothesized that the cost of 3D printer and 3D Printing material will be inversely proportional to the growth in the adoption of the technology.

To quantify this hypothesis, we examined 2 products: RFID and LED. Both RFID and LED are modern technologies that have made a significant impact on industry. Although RFID has existed for a number of years, it has been adopted in Supply Chain only over the last few years. As the adoption has increased, the price has come down, creating a positive feedback loop. Increased adoption has also led to the creation of industry standards. Similar trends have been

observed in LED. LED bulbs have been in the market for a few years now; however recent adoption of LED by large/medium organizations and governments has led to economies of scale and reduction in prices. Sections 4.1.2.1 and 4.1.2.2 below examine this growth.

4.1.2.1 RFID

Table 8 below shows as the adoption of RFID increased; correspondingly, the price changed from 0.75 USD in 2007 to 0.18 USD in 2014.

Table 8: Adoption of RFID

Year	Volume ($ Billion)	Price (USD)
2007	0.2	0.75
2008	0.3	0.6
2009	0.3	0.55
2010	0.5	0.45
2011	0.6	0.4
2012	0.7	0.35
2013	1.1	0.25
2014	1.9	0.18

Next, we performed regression analysis on the above data to calculate the Price/Volume relationship. Figure 8, below, shows the results of the regression analysis.

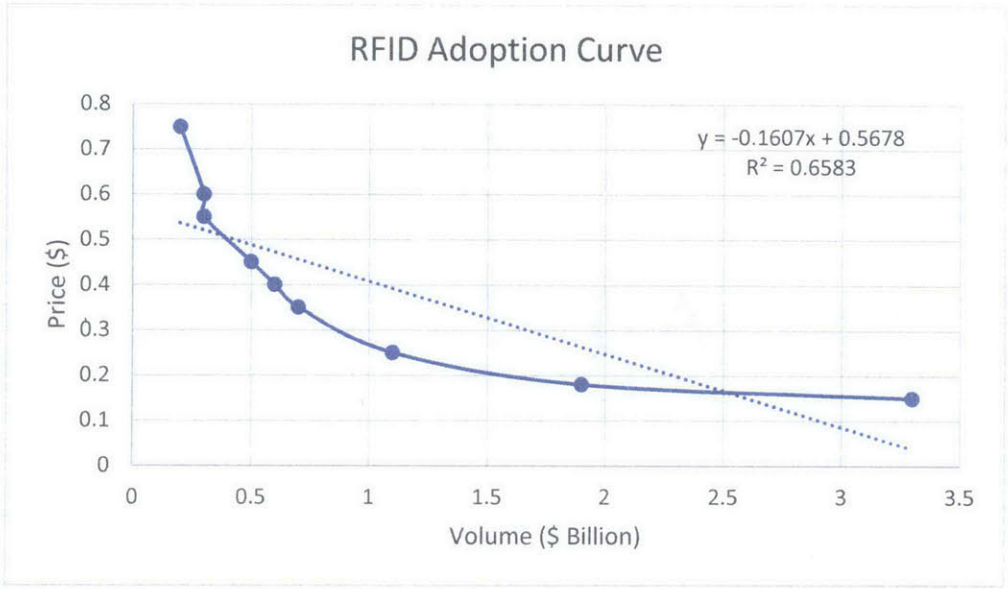


Figure 8: RFID Adoption Curve

From regression analysis, we got the following equation where (Price = y, Volume = x and R^2 = Coefficient of determination)

$$y = -0.1607x + 0.5678 \qquad (12)$$

$$R^2 = 0.6583$$

We will use this equation in Section 4.1.2.3 to estimate the adoption of 3D Printing.

4.1.2.2 LED

Table 9 below shows the increase in adoption of RFID and the corresponding change in price from 2009 to 2013

Table 9: Adoption of LED

Actual Year	Volume($ Million)	Price (USD)
2009	500	190
2010	750	120
2011	1200	95
2012	2000	80
2013	2500	65

Next we performed regression analysis on the above data to calculate the Price/Volume relationship. Figure 9 below shows the results of the regression analysis.

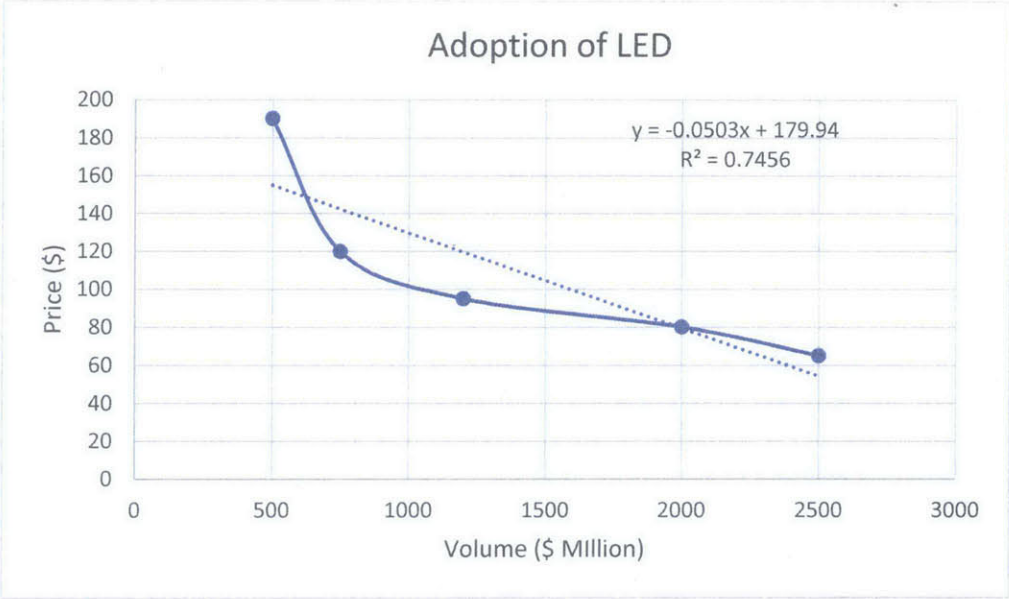


Figure 9: LED Adoption Curve

From regression analysis, we got the following equation where (Price = y, Volume = x and R^2 = Coefficient of determination)

$$y = -0.0503x + 179.94 \quad (13)$$

$$R^2 = 0.7456$$

We will use this equation in next section 4.1.2.3 to estimate the adoption of 3D Printing.

4.1.2.3 Future Projections

To determine the future projection for the cost of 3D Printing, we used the Price/Volume equation developed in Sections 4.1.2.1 & 4.1.2.2 and calculated the mean slope for RFID, and LED.

$$\text{RFID (Price = y, Volume = x)} \mid y = -0.1607x + 0.5678 \quad (12)$$

$$\text{LED (Price = y, Volume = x)} \mid y = -0.0503x + 179.94 \quad (13)$$

$$Mean\ Slope, m = -0.1055$$

We then fit the determined mean slope 'm' in the following linear equation:

$$y = mx + c \quad (14)$$

$$y = -0.1055x + c \quad (15)$$

Using above equation, we determined the future price projections of a 3D printed sample. Table 10 shows the projected growth in volumes of 3D Printing and the corresponding decrease in the cost of technology by economies of scale and adoption, taking 2012 as the baseline.

Table 10: Reduction in 3D Printing Cost Based on Increased Volumes

Year	Volume ($ Million)	Price (USD)	% Change
2012	800	1000	
2013	1000	979	2%
2014	1400	937	6%
2015	1700	905	9%
2016	2000	873	13%
2017	2500	821	18%
2018	3000	768	23%
2019	3600	705	30%
2020	4200	641	36%

Figure 10 below depicts 3D Printing growth and cost projection. It represents a 36% drop in the cost of 3D Printing. This will make 3D Printing even more affordable for low to medium volume products in the future.

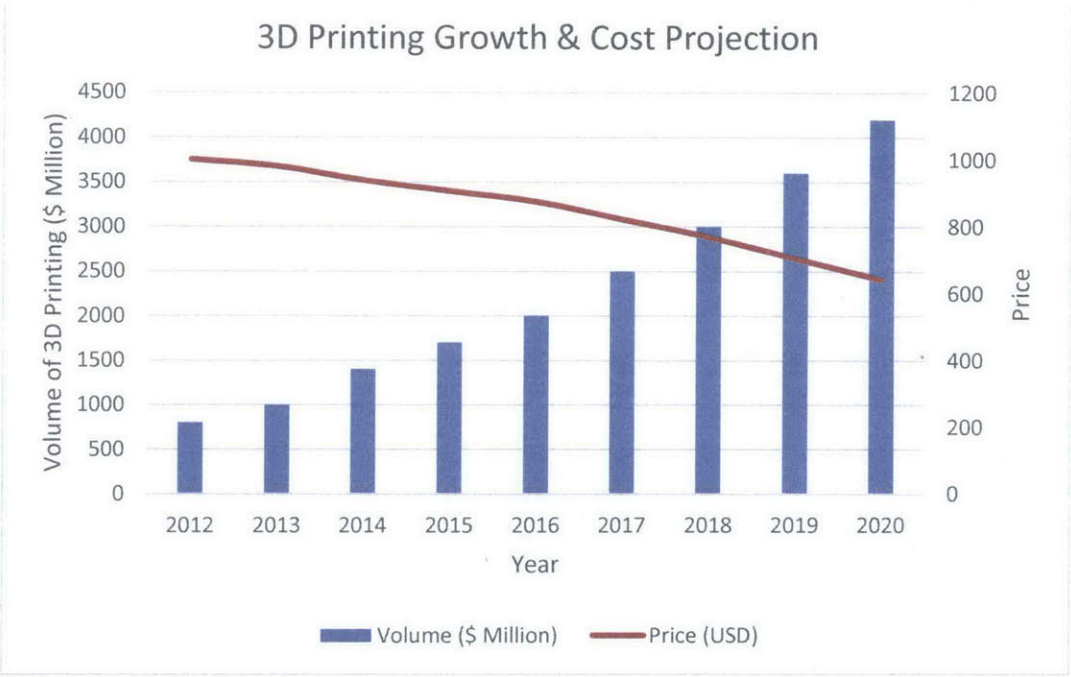


Figure 10: 3D Printing Growth and Cost Projection

4.2 Case I – Adoption of 3D Printing in a Regional Warehouse

In this case, we modeled the cost of the operations of a warehouse operated by a 3rd Party Logistics (3PL) Company. This case can be used as a model to provide 3D Printing facilities in the warehouses.

4.2.1 Study of existing Supply Chain Costs

When we visited the warehouse, we looked at the volume of goods flowing through the warehouse and the operational costs of the warehouse. To do so, we divided the SKUs into three categories: fast movers, slow movers and very slow movers. This is a regional warehouse. The

goods are manufactured in Asia and shipped to the warehouse and then distributed to end customers. We created a mathematical model based on the supply chain cost equations developed in Section 3.2. The purpose of this basic model was to get an overview of supply chain costs and apply them to specific cases (case 2 and 3) of Automotive and Life Sciences items.

For construction of this model, we used the variables and their sources listed in Table 11 below.

Table 11: List of Variables and Their Sources

Variable	Description	Source	Units	Calculation
c_1	Cost of transportation from Manufacturer to Asian Port	Secondary Research	$/mile	
c_2	Cost of transportation from Asian Port to US Port	Secondary Research	$/mile	
c_3	Cost of transportation from US Port to DC	Secondary Research	$/mile	
m_1	Miles from Manufacturer to Asian port	Assumed	Mile	
m_2	Miles from Asian Port to US Port	Assumed	Mile	
m_3	Miles from US Port to DC	Assumed	Mile	
n	Average No. of SKUs	Interviewee1		
V_t	Volume of 1 TEU (Twenty Foot Equivalent Unit)	Secondary Research	1360 cu ft	
V_p	Volume of a Spare Part	Assumed	1 cu ft	
S	Total Inbound Quantity	Interviewee1	TEU/yr	
n_p	No. of Parts Per TEU	Calculated	Units	V_t / V_p
i	No. of Inventory Turns	Calculated	/yr	
I_{avg}	Average Inventory On Hand	Calculated	TEU	S / i
k	Total Inventory Value	Interviewee1	$	
k_t	Average Cost of TEU	Calculated	$	k / I_{avg}
k_p	Average Cost Per Part	Calculated	$	k_t / n_p
L	Lead Time	Assumed	Yr	
K	Safety factor based on service level	Interviewee1		
I_{SKU}	Average Inventory On Hand per SKU	Calculated	Units	$(I_{avg})(n_p) / n$
J	Average Shelf Life	Interview	Weeks	

* Exhibit 5

4.2.1.1 Ordering Cost

Based on the information collected during the interviews, we concluded that there will be no change in ordering cost before and after the use of 3D Printing. Thus, ordering cost has not been included in the total supply chain cost comparison.

4.2.1.2 Transportation Cost

Using the secondary data available on internet, we calculated the cost of shipping incurred for transporting 1 Twenty Foot Equivalent Unit (TEU).

$$\text{Transportation Cost } \left(\frac{\$}{\text{yr}}\right) = S\ C_t \qquad (16)$$

where

S = Total inbound quantity $\left(\frac{\text{TEU}}{\text{yr}}\right)$

C_t = Cost of shipping 1 TEU from manufacturer to DC $\left(\frac{\$}{\text{TEU}}\right)$

Table 12 below gives the transportation cost to ship a TEU from Asia (China) to Louisville, KY (assumed location of the warehouse) and then to a customer.

Table 12: Transportation Cost Calculations

Transportation Cost		
China - California	Export Costs	$923
(By Ship TEU)	Transit Costs	$4,000
1360 cu ft	Import Costs	$1,315
	Total Costs	$6,238
LA - Louisville, KY	Rail ($0.35 Per mile for 2000 miles)	$700
(By Intermodal)	Transfer	$150
	Dayrage	$100
Louisville, KY – Dealers	Freight Cost ($1.8 Per Mile for 400 miles)	$720
(By Truck)		
Total Transportation cost per TEU		**$14,146**

4.2.1.3 Inventory Holding Cost

We calculated the annual inventory holding cost for items held at the warehouse.

$$\text{Inventory Holding Cost } \left(\frac{\$}{\text{yr}}\right) = k_t \, r \, I_{avg} \qquad (16)$$

where

$i = \text{No. of Inventory Turns } \left(\frac{}{\text{yr}}\right)$

$I_{avg} = \text{Average Inventory On Hand (TEU)} = \frac{S}{i}$

$k = \text{Total Inventory Value (\$)}$

$k_t = \text{Average Cost of TEU} = \frac{k}{I_{avg}}$

$$k_p = \text{Average Cost per Part} = \frac{k_t}{n_p}$$

To compute the inventory holding cost rate *r,* we researched the industry standard for average inventory carrying cost. Based on research (Johnson & Wood, 1986), we took 25% to be the average inventory holding cost for all calculations.

4.2.1.4 Pipeline Inventory Cost

We calculated pipeline inventory cost for the inventory in transit.

$$\text{Pipeline Inventory Cost } \left(\frac{\$}{\text{yr}}\right) = k_t\, r\, (S\, L) \qquad (17)$$

where

$$\text{Demand over Lead Time} = S * L$$

$$I_{SKU} = \text{Average Inventory On Hand per SKU} = \frac{(I_{avg})(n_p)}{n}$$

$$j = \text{Average Shelf Life}$$

Table 13 below shows the details of lead times.

Table 13: Lead Times for Shipping

Lead Time		
Manufacturing Lead Time	12	weeks
Shipping Time (China - California)	5	weeks
US Port - US DC	1	weeks
DC – Dealer	1	day

Source: Data collected during site visit and interviews at the warehouse

4.2.1.5 Total Cost

By adding all supply chain cost elements, we calculated the total supply chain cost using equation 1 described earlier in section 3.2

$$Total\ Cost = Purchase\ or\ manufacturing\ Cost + Order\ Cost + Transportation\ Cost + Inventory\ Holding\ Cost + Pipeline\ Inventory\ Cost + Stock\ Out\ Cost \quad (1)$$

Table 14 below shows the calculations of total cost.

Table 14: Total Cost Calculations for Traditional Manufacturing

Warehouse Data		
Average Number of SKU	40,000	
Total Inventory value	$30,000,000	
No of Inventory Turns	5	
Total Inbound Quantity Per Month	250	TEU
Total Inbound Quantity Per Year	3,000	TEU
Average Inventory on hand	600	TEU
Average cost per TEU	$50,000	

Source: Data collected during site visits and interviews at the warehouse

Volume Conversion		
1 TEU	1,360	cu ft
1 EA Part	1.0	cu ft
# of Parts Per TEU	1,360	

Source: Data & assumptions based on site visits and interviews at the warehouse

	Fast Movers	Slow Movers	Very Slow Movers
# of SKU	2,500	17,500	20,000
% of SKU Volume Sold	40%	40%	20%
Average Inventory on hand (TEU)	240	240	120
Average Inventory on hand per SKU (EA)	131	19	8
Avg. Shelf Life (Weeks)	2	12	26
Total Inventory Cost	$3,000,000	$3,000,000	$1,500,000
Total Pipeline Inventory Cost	$1,730,769	$1,730,769	$865,385
Total Transportation Cost	$16,975,200	$16,975,200	$8,487,600
Total Supply Chain Cost	**$21,705,969**	**$21,705,969**	**$10,852,985**

4.2.2 Study of Supply Chain Costs with Adoption of 3D Printing

The adoption of 3D Printing will change the total supply chain costs calculated in section 4.3.1. To calculate this impact, we assumed that 3D Printing will be largely adopted for very slow movers and slow movers. However, fast movers will have a very low level of adoption because of lack of economies of scale. Table 15 below depicts these 3D Printing adoption percentages.

Table 15: 3D Printing Adoption Percentages

Product Category	3D Printing Adoption
Fast Movers	10%
Slow Movers	25%
Very Slow Movers	60%

The second major change will be seen in the transportation cost. For a 3D printed SKU in the warehouse, the transportation cost will be the cost of transporting raw material used. This will be significantly less than the cost of transporting the finished SKU from Asia. Table 16 below shows the calculations for transportation cost.

Table 16: Transportation Costs

Transportation Cost					
Type	**Route**	**Type**	**Cost/Mile**	**Miles**	**Cost**
Raw Material	Steel Manufacturer - Louisville, KY (By Truck)	Freight Cost	$1.8	1,000	$1,800
Transportation Cost for Raw Material					$1,800
Finished Products	Louisville, KY Dealers (By Truck)	Freight Cost	$1.8	400	$720
Transportation Cost for Finished Products					**$720**
Total Transportation cost per TEU					**$2,520**

Table 17 below shows the total supply chain cost calculations for the warehouse after adoption of 3D Printing.

Table 17: Total Cost Calculations for Manufacturing after adoption of 3D Printing

Warehouse Data		
Average Number of SKU	40,000	
Total Inventory value Finished Goods on Hand	$22,200,000	
Total Inventory value Raw Material on Hand	$2,574,000	
No of Inventory Turns	5	
Average Inventory on hand (Level to be maintained)	600	TEU
Average Inventory on hand - Finished Goods	444	TEU
Average Inventory on hand - Raw Material	31	TEU
Average cost per TEU - Finished Goods	$50,000	
Average cost per TEU - Raw Material	$82,500	

Volume Conversion		
1 TEU	1,360	cu ft.
1 EA Part Raw Material	0.20	cu ft.
# of Parts Per TEU Raw Material	6,800	
1 EA Part Finished	1.00	cu ft.
# of Parts Per TEU Finished	1,360	
Raw Material : Finished Goods Volume	0.20	
Raw Material : Finished Goods value	0.33	

	Fast Movers	Slow Movers	Very Slow Movers
# of SKU	2,500	17,500	20,000
% of Volume Sold	40%	40%	20%
3D Printing	25%	60%	90%
Total Inventory on Hand (Level to be Maintained)	240	240	120
Average Inventory on hand - Finished Products (TEU)	180	96	12
Average Inventory on hand per SKU - Finished Products (EA)	131	19	8
Average Shelf Life - Finished (Weeks)	2	12	26
Average Inventory on hand - Raw Material (TEU)	12.00	28.80	21.60
Average Inventory on hand per SKU - Raw Material (EA)	131	19	8
Average Shelf Life - Raw Material (Weeks)	0.5	0.5	0.5
Total Inventory Cost	$2,497,500	$1,794,000	$595,500
Total Pipeline Inventory Cost	$1,440,865	$1,035,000	$343,558
Total Transportation Cost	$2,592,000	$1,987,200	$734,400
Total Supply Chain Cost	**$6,530,365**	**$4,816,200**	**$1,673,458**

4.2.3 Conclusion for Warehouse Case

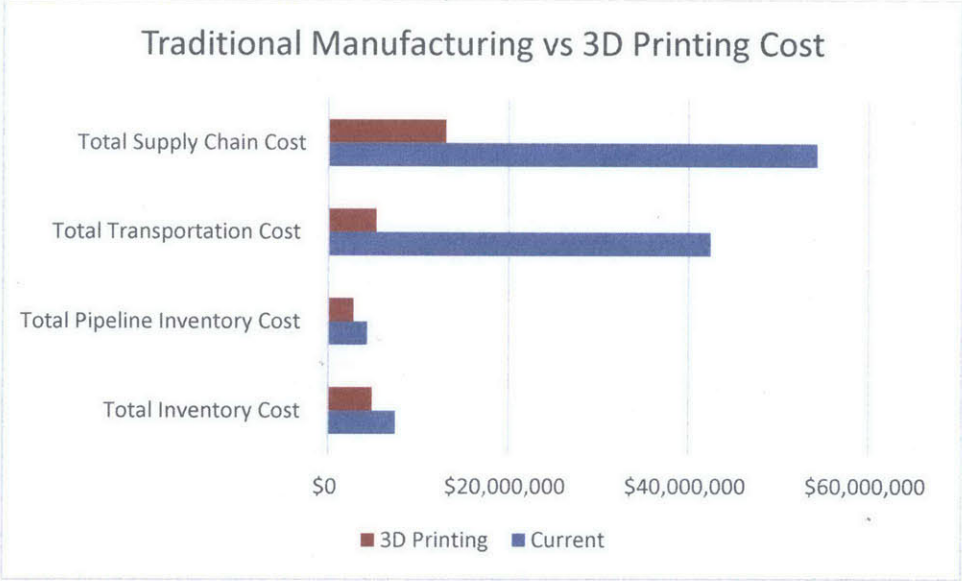
Table 18 below shows the comparison of the three main components of total supply chain costs for the current and future scenario (adoption of 3D Printing) for all the SKUs i.e., Fast Movers, Slow Movers and Very Slow Movers combined together

Table 18: Supply Chain Cost Components for Warehouse Case

Scenario	Current	3D Printing	% Savings
Inventory Cost	$7,500,000	$6,193,500	17%
Pipeline Inventory Cost	$4,326,923	$3,573,173	17%
Transportation Cost	$42,438,000	$6,436,800	85%
Total Supply Chain Cost	**$54,264,923**	**$16,203,473**	**70%**

Figure 11 below shows the cost comparison of traditional manufacturing and 3D Printing.

Figure 11: Cost Comparison of Traditional Manufacturing and 3D Printing for Warehouse



We observe a significant saving of 17% respectively in the Inventory Cost and Pipeline Inventory Cost. This is largely due to warehouse holding less stock. The major savings of 85% however comes from Transportation cost due to reduced shipping costs from Asia. Overall we project a savings of 70% in the total supply chain costs.

Table 19 below shows the total cost by product category. The greatest percent saving is observed in very slow moving product category, which strengthens our original hypothesis that 3D Printing is more suitable for low volume manufacturing. Figure 12 below depicts it graphically.

Table 19: Total Supply Chain Cost by Product Category for Warehouse Case

	Total Supply Chain Cost		
	Traditional Manufacturing	3D Printing	% Saving
Fast Movers	$21.7	$6.5	70%
Slow Movers	$21.7	$4.8	78%
Very Slow Movers	$10.9	$1.7	85%

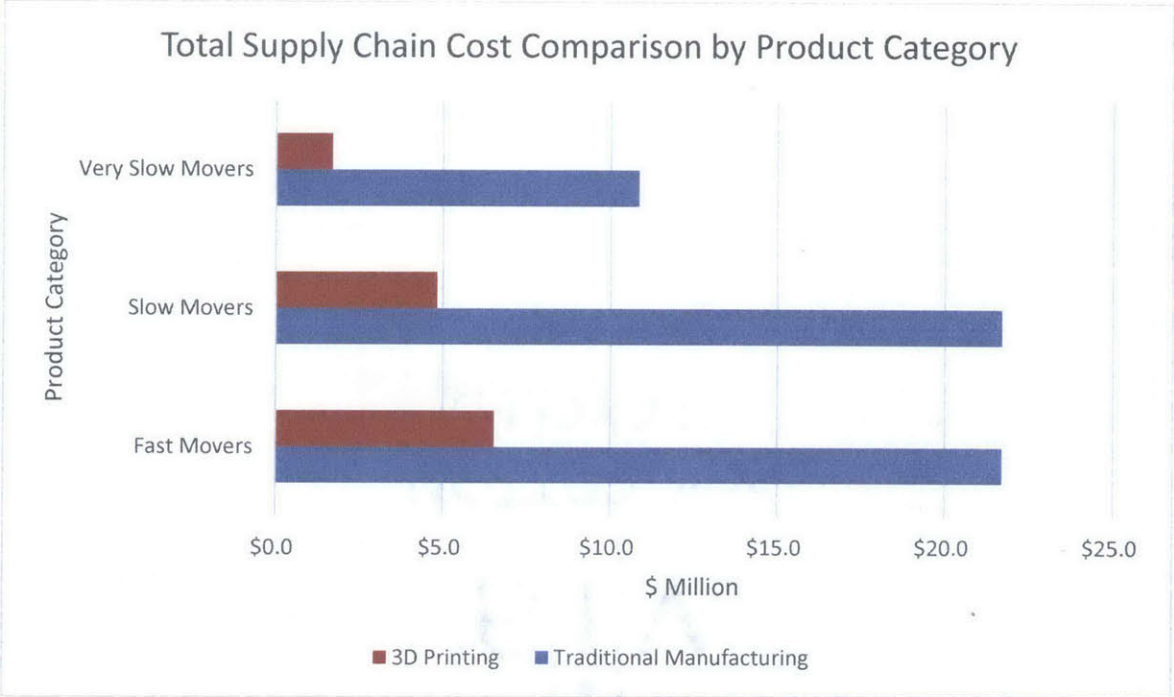


Figure 12: Total Supply Chain Cost Comparison by Product Category

As a next step, we performed a sensitivity analysis to compare the total supply chain cost for 3D Printing under three different adoption scenarios. Table 20 below depicts the percentage ranges for 3D Printing adoption scenarios and Figure 13 shows the sensitivity analysis.

Table 20: 3D Printing Adoption Scenarios

3D Printing Adoption Scenarios			
Product Category	**Low**	**Med**	**High**
Fast Movers	0%	10%	25%
Slow Movers	10%	25%	60%
Very Slow Movers	25%	60%	90%

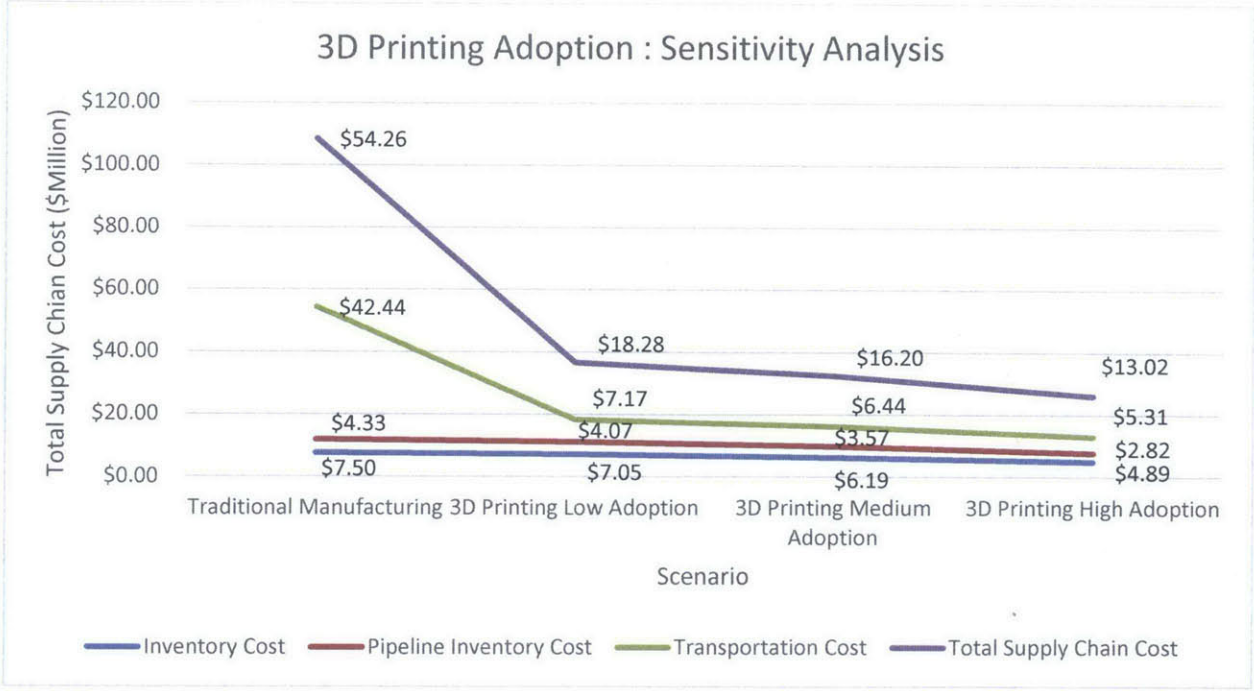


Figure 13: Sensitivity Analysis for 3D Printing Adoption

4.3 Case II- Automotive Industry

In this case, we calculated the total supply chain costs and potential savings from transitioning a low volume, very slow mover Automotive part from traditional manufacturing to 3D Printing. This case shows how 3PL companies can create value by offering 3D Printing services.

This warehouse is a regional warehouse of a car maker. Currently the goods are manufactured in Asia and shipped to the warehouse and then distributed to a car dealer where they are installed in customer vehicles. The warehouse has daily deliveries to all car dealers in the region.

In this case we propose that 3D Printing facilities be installed in warehouses. Once a car dealer order is received, the ERP system will determine if it is a pick product (in inventory) or a 3D Print product. For a pick product, a normal pick and pack process will be initiated, as it occurs today. For a 3D print product, a command will be sent to the 3D printer to manufacture the

product. The 3D printer will confirm the order and send a pick up time. A pick order for the product will then be created from the 3D Print location.

4.3.1 Study of existing Supply Chain Costs

To calculate the costs, we used the data provided during our interviews at the warehouse and the mathematical model equations developed in Section 3.2

4.3.1.1 Transportation Cost

Table 21 below shows the calculation of transportation cost to ship a TEU from Asia (China) to Louisville, KY (assumed location of the warehouse).

Table 21: Transportation Cost Calculations

Transportation Cost (Manufacturer - Warehouse)		
China - California	Export Costs	$923
(By Ship TEU)	Transit Costs	$4,000
1360 cu ft	Import Costs	$1,315
	Total Costs	$6,238
LA - Louisville, KY	Rail ($0.35 Per mile for 2000 miles)	$700
(By Intermodal)	Transfer	$150
	Dayrage	$100
Transportation cost per TEU		$13,426
Surcharge of Less than Full TEU		50%
Transportation cost per TEU for Less than Full		$20,139
Cost per cu ft.		**$14.8**

Transportation Cost (Warehouse - Dealers)		
Louisville, KY – Dealers	Freight Cost ($1.8 Per Mile for 400 miles)	$720
(By Truck)		
Surcharge for LTL		50%
Cost Per cu ft.		**$0.79**

Volume Conversion		
1 TEU	1,360	cu ft.
1 EA Part	1.0	cu ft.

4.3.1.2 Supply Chain Cost Calculation

Table 22 below depicts the calculation of total supply chain cost for case II.

Table 22: Supply Chain Cost Calculation for Automotive

Traditional Manufacturing			
Item	**Identifier**	**Value**	**Unit**
Purchase Cost	V	100	$/unit
Average Total Annual Demand	D	1,200	units/year
Inventory holding cost	R	25%	of cost
Order Frequency		6	Per Year
Order Quantity	Q	200	units/order
Transportation Cost		16	$/unit
Lead time	L	6	Week
Purchase Cost		$120,000	$/year
Transportation Cost		$18,723	$/year
Inventory Holding Cost		$2,500	$/year
Pipeline Inventory Cost		$3,462	$/year
Total Cost		**$144,684**	**$/year**
Cost Per item		**$121**	

Source: Data & assumptions based on site visit and interviews at warehouses

4.3.2 Study of Supply Chain Costs after adopting 3D Printing

In this case, we transitioned the entire manufacturing to 3D Printing. Orders are placed daily by the car dealers. The product is then 3D Printed and delivered. There is no product inventory. Table 23 shows the supply chain costs after adopting 3D Printing.

Table 23: Supply Chain Cost Calculation after adoption of 3D Printing

3D Printing			
Item	**Identifier**	**Value**	**Unit**
Purchase Cost of Knee Implant	V	80	$/unit
Average Total Annual Demand	D	1,200	units/year
Inventory holding cost	R	25%	of cost
Order Frequency		365	Per Year
Order Quantity	Q	3	units/order
Transportation Cost		1	$/unit
Lead time	L	2	Day
Purchase Cost		$96,000	$/year
Transportation Cost		$953	$/year
Inventory Holding Cost		$33	$/year
Pipeline Inventory Cost		$132	$/year
Total Cost		**$97,117**	**$/year**
Cost Per item		**$81**	

Source: Data & Assumption based on site visit and interview at warehouses

4.3.3 Conclusion for Automotive Case

Table 24 below shows a comparison of the components of supply chain costs for the current and future scenario (adoption of 3D Printing).

Table 24: Cost Comparison between Traditional Manufacturing and 3D Printing

Scenario	Traditional Manufacturing	3D Printing	% Savings
Purchase Cost	$120,000	$96,000	20%
Transportation Cost	$18,723	$953	95%
Holding Cost	$2,500	$33	99%
Pipeline Cost	$3,462	$132	96%
Total Product Cost	**$144,684**	**$97,117**	**33%**

Scenario	Traditional Manufacturing	3D Printing	% Savings
Product Cost	$121	$81	33%

Figure 14 below depict a cost comparison of traditional manufacturing and 3D Printing.

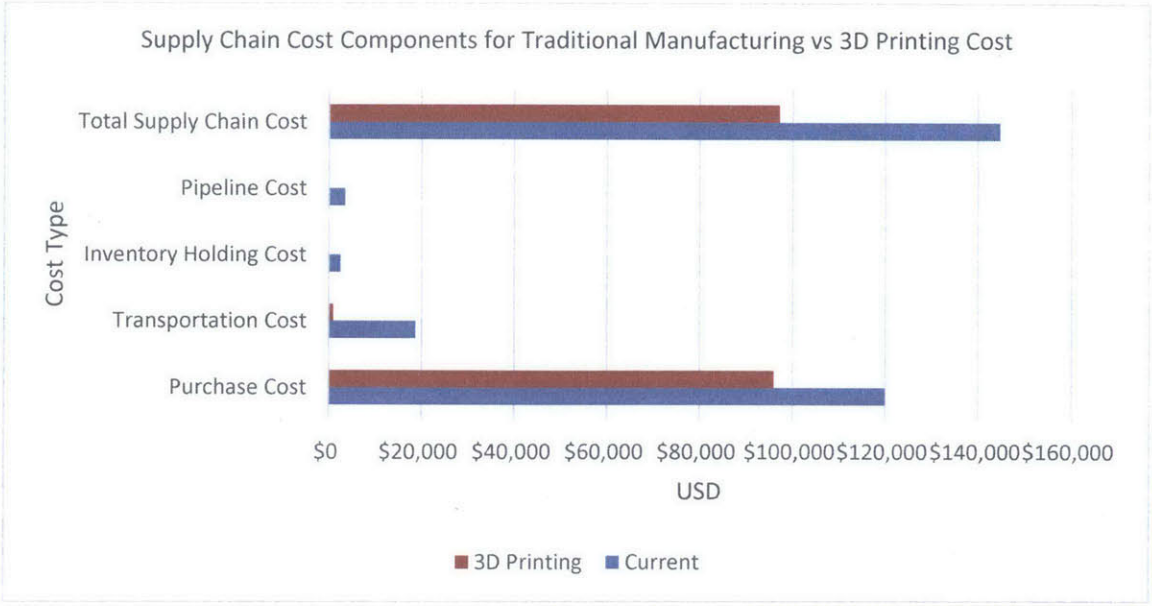


Figure 14: Cost Comparison of Traditional Manufacturing and 3D Printing for Automotive

We observed a significant saving of over 90% coming from Inventory Holding Cost and Pipeline Inventory Cost and Transportation Cost. The savings in Inventory Holding Cost and Pipeline Inventory Cost can be attributed to the warehouse holding virtually no stock as everything is being manufactured on demand. Another major savings of 95% comes from Transportation Cost due to reduced shipping costs. With the manufacturing being done in the warehouse, the Transportation Cost is reduced to the cost of moving the product from the warehouse to car dealers. The actual product cost is also projected to come down by 20%. We have observed in our research that for Automotive parts with low volume, the cost of 3D Printing is actually lower than traditional manufacturing. Interviews with 3D Printing experts have suggested that this can be as much as 20%. Overall we project savings of 33% in the Total Product Costs.

While cost savings is one motivator for adoption of 3D Printing, the other major advantage is the speed to market. By adopting 3D Printing, car manufacturers do not need to stock low volume spare parts of older models and can still provide a 100% item fill rate in a very short lead time of

2 days and keep their customers happy. As we had observed earlier in our discussion because sales at spare parts have a much higher profit margin than cars themselves, the improvement in the availability of spare parts by adoption of 3D Printing can lead to an increase in the market share of OEMs in the spare parts business.

We conclude that adoption of 3D Printing can have a significant impact on the spare parts business in 3 ways:

- Reduction in Total Product Cost
- Improvement in product availability, leading to higher customer satisfaction
- Potential increase in market share in the spare parts business

4.4 Case III- Life Sciences Industry

In this case, we compared the total supply chain costs of a Life Sciences part - a knee implant - manufactured by traditional manufacturing against that of 3D Printing. We assumed that this healthcare facility is a medium sized hospital. In the current scenario, knee implants are manufactured in Asia and then they are shipped to this warehouse and distributed to hospitals. The warehouse has daily deliveries to all hospitals in the region via sales professionals.

We propose that 3D Printing facilities be installed in warehouses. Once a hospital order is received, the ERP system will determine if it is a pick product (in inventory) or a product to be 3D printed. For a product available in inventory, normal picking and packaging process will be initiated. However, for a 3D Print product, the 3D Printer will be prompted to manufacture it.

4.4.1 Study of existing Supply Chain Costs

To calculate the costs, we used the data collected during our interviews at the warehouse and the mathematical model equations developed in Section 3.2.

4.4.1.1 Transportation Cost

This cost has been calculated to transport the knee implant from Asian port assumed as China to California and from California to the warehouse in Louisville, KY (assumed location). Table 25 below shows the calculation of the Transportation Cost.

Table 25: Transportation Cost Calculations

Transportation Cost (Manufacturer - Warehouse)		
China - California	Export Costs	$923
(By Ship TEU)	Transit Costs	$4,000
1360 cu ft	Import Costs	$1,315
	Total Costs	$6,238
LA - Louisville, KY	Rail ($0.35 Per mile for 2000 miles)	$700
(By Intermodal)	Transfer	$150
	Dayrage	$100
Transportation cost per TEU		$13,426
Surcharge of Less than Full TEU		50%
Transportation cost per TEU for Less than Full		$20,139
Cost per cu ft.		**$14.8**

Transportation Cost (Warehouse - Dealers)		
Louisville, KY – Hospitals	Freight Cost ($1.8 Per Mile for 400 miles)	$720
(By Truck)		
Surcharge for LTL		50%
Cost Per cu ft.		**$0.79**

Volume Conversion		
1 TEU	1,360	cu ft.
1 EA Part	1.0	cu ft.

4.4.1.2 Supply Chain Cost Calculation

The total supply chain costs included all relevant costs namely Purchase Cost, Transportation Cost, Inventory Holding Cost and Pipeline Inventory Cost. Since Ordering Cost in the case of traditional manufacturing and 3D Printing will remain the same, we have not included it in our analysis. Table 26 below shows the supply chain cost calculation.

Table 26: Supply Chain Cost Calculation for Case III

Traditional Manufacturing			
Item	**Identifier**	**Value**	**Unit**
Purchase Cost	V	5,000	$/unit
Average Total Annual Demand	D	120	units/year
Inventory holding cost	R	25%	of cost
Order Frequency		6	Per Year
Order Quantity	Q	20	units/order
Transportation Cost		15.6	$/unit
Lead time	L	6	Week
Purchase Cost		$600,000	$/year
Transportation Cost		$1,872	$/year
Inventory Holding Cost		$12,500	$/year
Pipeline Inventory Cost		$17,308	$/year
Total Cost		**$631,680**	**$/year**
Cost Per item		**$5,264**	

Source: Data & assumptions based on site visits and interviews at warehouses

4.4.2 Study of Supply Chain Cost after adopting 3D Printing

In this case, we switch from traditional manufacturing to 3D Printing and do not stock inventory of the product. Orders are placed daily by the hospitals, and the products (knee implants) are then 3D Printed and delivered to the hospitals. Table 27 below shows these costs.

Table 27: Supply Chain Cost Calculation after adoption of 3D Printing

3D Printing			
Item	**Identifier**	**Value**	**Unit**
Purchase Cost	V	2,000	$/unit
Average Total Annual Demand	D	120	units/year
Inventory holding cost	R	25%	of cost
Order Frequency		120	Per Year
Order Quantity	Q	1	units/order
Transportation Cost		0.79	$/unit
Lead time	L	2	day
Purchase Cost		$240,000	$/year
Transportation Cost		$95	$/year
Inventory Holding Cost		$250	$/year
Pipeline Inventory Cost		$329	$/year
Total Cost		**$240,674**	**$/year**
Cost Per item		**$2,006**	

Source: Data & assumptions based on site visits and interviews at warehouses

4.4.3 Conclusion for Life Sciences Case

Table 28 below shows a comparative analysis of the four main components of supply chain costs for traditional manufacturing and the future scenario of 3D Printing.

Table 28: Cost Comparison of Traditional Manufacturing and 3D Printing – Case III

Scenario	Current	3D Printing	% Savings
Purchase Cost	$600,000	$240,000	60%
Transportation Cost	$1,872	$95	95%
Inventory Holding Cost	$12,500	$250	98%
Pipeline Cost	$17,308	$329	98%
Total Supply Chain Cost	**$631,680**	**$240,674**	**62%**

Scenario	Current	3D Printing	% Savings
Product Cost	$5,264	$2,006	62%

Figure 15 below depicts cost comparison of traditional manufacturing and 3D Printing graphically.

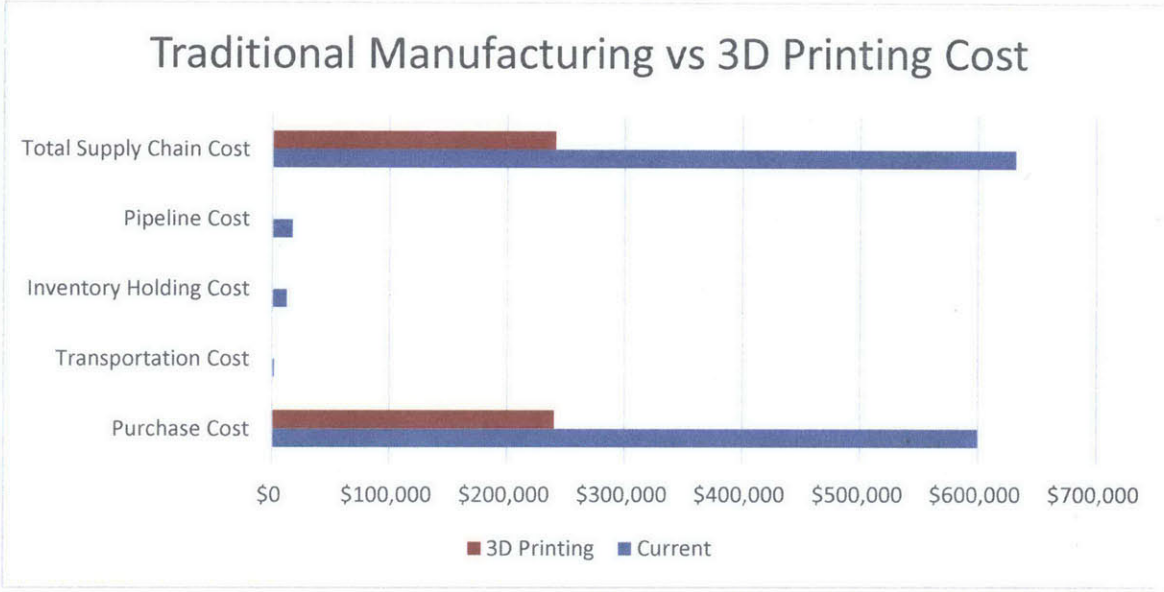


Figure 15: Cost Comparison of Traditional Manufacturing and 3D Printing for Life Sciences

In case of 3D Printing, there is a significant saving over 90% in case of Inventory Holding Cost, Pipeline Inventory Cost and Transportation Cost. Since there is no stock held in the warehouse, Inventory Holding Cost and Pipeline Inventory Cost have reduced to almost nothing. Transportation cost has also dropped because the product is printed in the warehouse and shipped to the hospital as compared to shipping it all the way from China. Product cost is also expected to come down by 60% (3D Printing Expert, 2014). Overall we foresee a savings of 62% in the total supply chain costs.

Besides cost savings, there are other associated benefits of 3D Printing. They include speed to market and supply chain agility due to postponement. By use of 3D Printing, healthcare facilities or Life Sciences warehouses do not need to stock inventory of highly customized medical implants and surgical devices and can still provide a 100% service level.

In short, adoption of 3D Printing by the Life Sciences industry will benefit companies in the following ways:

- Reduction in total supply chain cost
- Improvement in product availability, yielding higher service levels and customer satisfaction

4.5 Limitations of Methodology

In this thesis we have created a quantitative model to estimate the impact of 3D Printing on supply chains of future, in particular, Automotive and Life Sciences industry. However there are limitations to our research.

We have used a number of cases and examples to create our model; thus the model is biased towards the industries and geographies from which the data has been taken.

The data for the presented cases has been gathered from a limited number of sources which were recommended by our thesis sponsor. Thus the data used may not be a very good sample.

While computing the cost differences between traditional manufacturing and 3D Printing, we have taken cases where injection molding was considered as the traditional manufacturing method. We understand that there are number of other techniques and cost calculation for these techniques can vary hugely. In the case of 3D Printing, we have assumed a uniform cost for materials.

We have also not taken into account the quality aspects of 3D Printing and the time it takes to manufacture via 3D Printing vs. Injection Molding. For industries such as Automotive and Life

Sciences, each 3D Printing facility will have to be individually tested to ensure the quality of the end product. This may have an impact on the total product cost.

In computing the total supply chain costs, we assumed that raw materials for 3D Printing will be available locally; this may not hold true for all materials.

5. Discussion

The results presented in Section 4 indicate that 3D Printing can be a disruptive technology for the manufacturing and logistics industries especially in the low volume custom products segment. 3D Printing will change the supply chain cost equation reducing inventory and transportation cost. This threat also presents a unique opportunity for companies to make their supply chains efficient and for 3PL companies to offer 3D Printing services.

5.1 Difficulty of Quantifying the Impact of 3D Printing on Supply Chain

3D Printing in the early days was very expensive and the major application of 3D Printing was limited to prototyping for new products (The History of 3D Printing, 2014). The increasing adoption of 3D Printing technology and a subsequent drop in the price has led to a number of new applications. Most of the new applications have been in low volume custom designed products, permitting manufacturing of one product at a time without a huge initial setup cost.

The overall adoption of 3D Printing by various industries is still very limited. In our research and industry interactions, we found that though companies are excited about the prospect of 3D Printing in the future, not many have moved from traditional manufacturing to 3D Printing. It was thus really challenging to make assumptions around the industry adoption numbers in our model.

According to Gartner Hype Cycle for Emerging Technologies 2013, which describes the adoption of new technologies in the industry, it will take 2-5 years for enterprise 3D Printing to reach "plateau of productivity". Most of the 3D printers in the market today are only suited for very small batch sizes and take a long time to manufacture a single item. Enterprise manufacturing even at low volume quantities of 100 items per day is still challenging.

There are also major concerns about the finished quality of the product and the materials that can be used for 3D Printing. The industry standards are still very raw and most of the technology is patented by 3D printer manufacturing companies.

With the concerns described above, we found it very difficult to predict how the 3D Printing cost structure will change over the next 5-10 years. This is especially related to the cost of 3D Printers and the raw material used. We assumed that in the next 5-10 years, 3D Printing technology will evolve sufficiently to be able to manufacture most of the products that are today manufactured using a variety of manufacturing techniques and a range of materials including metals, alloys, ceramics and plastics. The practical application of 3D Printing will require designers to think very differently. Due to the above limitations, projection of future cost models was really challenging and we had to rely on similar technology adoptions curves for RFID and LED. Also it is not clear at this point if the cost structure for 3D Printing will vary according to the type of material. In our models, we have assumed it to be the same for all materials used in future.

Government policies, offshoring practices, availability of talent and raw materials will be some of the other critical factors that will impact the future adoption of 3D Printing.

We can argue with sufficient confidence that adoption of 3D Printing will grow in low volume customized products. The question is: Will this be a new category of products or will 3D Printing displace some of the products that are today being manufactured by traditional methods, and if so what will be volume of the change?

5.2 Impact on Logistics Industry

Third Party Logistics (3PL) companies offer two basic services, Freight Management and Contract Logistics. Freight Management includes transporting products by land, air and sea,

securing space with shipping companies and airlines, and handling all the administrative work such as Customs. Contract Logistics includes a host of services such as warehouse management, returns processing and other value added services such as kitting.

With the adoption of 3D Printing, the major impact will be on the freight revenues. Based on the results presented in Section 4.2.3, Table 16a, the total transportation spent by a warehouse may be reduced by up to 85%. For a 3PL company, this means a direct loss of 85% of the revenue from the Freight Business. For a typical Freight Management company that does not offer Contract Logistics, this will significantly reduce revenues and deplete the economies of scale it enjoys today, leading to an increase in costs. This may lead to challenging situations for these companies. For a 3PL company that offers both Freight Management and Contract Logistics, this will be an opportunity to expand the value added service offerings by offering 3D Printing services in the warehouse. By providing such services, the 3PL will be able to balance the lost revenue from the Freight business and the gained revenue from the 3D Printing services. The margins in the value added services business are much higher than Freight, the 3PL companies should be able to hold on to their margins even at the loss of revenue from the Freight business.

Providing 3D Printing facilities and offering customers expertise to adopt 3D Printing to improve supply chain efficiency and develop custom products can be a big competitive advantage for 3PL companies in the future.

5.3 Opportunities for Future work

The models developed in this thesis are a good starting point for understanding the supply chain costs if 3D Printing technology is adopted in the Automotive and Life Sciences industries.

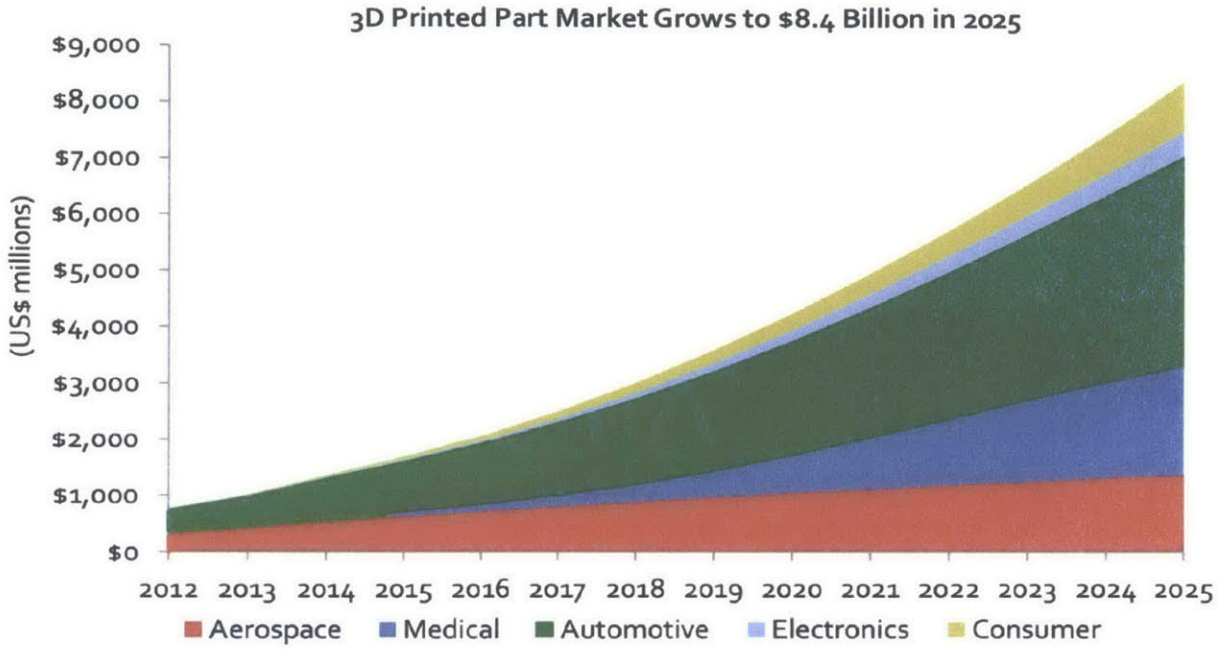
The data used to develop the models presented in this thesis is limited to a small sample of products from a handful of companies from the two industries in North America. As a next step we propose to look into a larger breadth of companies and products.

The models we have developed only consider direct costs, for a better assessment of cost savings we also need to consider indirect costs such as quality control, design, testing and government regulations.

The model developed in this research is not restricted to life sciences and automotive industry. Rather, the insights can be applied across virtually every industry that wants to adopt 3D Printing.

6. Exhibits

Exhibit 1



Source: Lux Research, Inc.

Exhibit 2

FY 2013 in Billion Euro

DHL Business Unit	Revenues	EBIT	% EBIT	Operating Margin
MAIL	14.45	1.22	37.3%	8.4%
Express	12.71	1.13	34.6%	8.9%
Global Freight Forwarding	14.83	0.48	14.7%	3.2%
Supply Chain	14.27	0.44	13.5%	3.1%

Exhibit 3

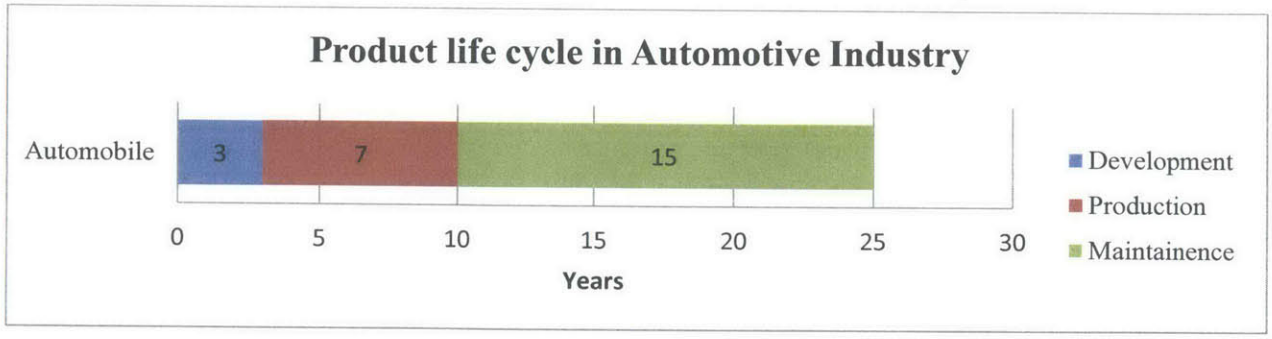


Exhibit 4

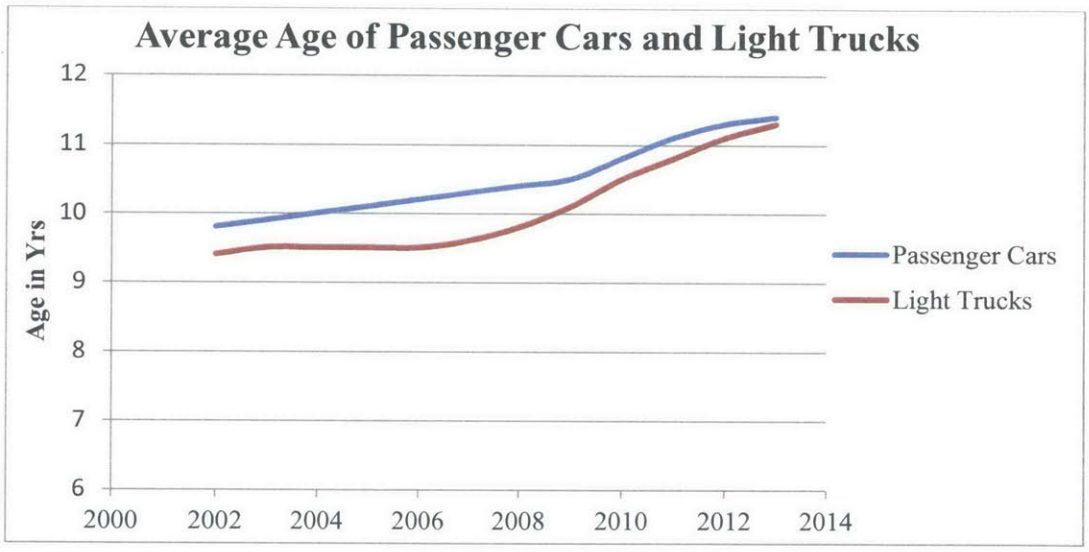


Exhibit 5

Interviewee	Company	Area of Expertise
Interviewee 1	Japanese Car Manufacturer	Warehouse Management
Interviewee 2	Thesis Sponsor	Logistics & Transportation
Interviewee 3	Thesis Sponsor	Logistics & Transportation
Interviewee 4	Thesis Sponsor	Logistics & Transportation
Interviewee 5	Medical Implants Manufacturer	Supply Chain Management
Interviewee 6	Thesis Sponsor	Auto Supply Chain Management Specialist
Interviewee 7	Thesis Sponsor	Life Sciences Supply Chain Management Specialist

Exhibit 6

List of 3D Printing Company
makexyz.com
Sculpteo
3dprintuk
Shapeways
Panashape.com

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