# Additive Versus Traditional Manufacturing: A Techno-Economic Analysis of Printed Circuit Boards and Pistons

A Major Qualifying Project
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**Table of Authorship**

| **Section Title** | **Primary Author** | **Page** |
|---|---|---|
| Abstract | Cheyenne | 7 |
| 1.0 Introduction | Cheyenne | 7 |
| 2.0 Background | Cheyenne | 9 |
| 2.1 Traditional Manufacturing | Cheyenne | 9 |
| 2.2 Additive Manufacturing | Matt | 11 |
| 2.3 Electronic Industry | Cheyenne | 12 |
| 2.4 Automotive Industry | Matt | 15 |
| 3.0 Methodology | Cheyenne | 17 |
| 3.1 Case Study 1 Approach: PCBs | Cheyenne | 17 |
| 3.1.1 PCB Cost Model | Cheyenne | 20 |
| 3.1.2 PCB Life Cycle Analysis | Cheyenne | 22 |
| 3.2 Case Study 2 Approach: Piston | Cheyenne | 25 |
| 3.2.1 Piston Cost Model | Matt | 27 |
| 3.2.2 Piston Life Cycle Analysis | Matt | 28 |
| 4.0 Results and Analyses | Cheyenne | 29 |
| 4.1 Resulting PCB Cost Models | Cheyenne | 30 |
| 4.1.1 Traditional PCB Cost Model | Cheyenne | 30 |
| 4.1.2 Additive PCB Cost Model | Cheyenne | 33 |
| 4.1.3 PCB Cost Model Comparison | Cheyenne | 36 |
| 4.2 Resulting PCB Life Cycle Analyses | Cheyenne | 38 |
| 4.3 Resulting Piston Cost Model | Matt | 44 |
| 4.3.1 Traditional Piston Cost Model | Matt | 45 |
| 4.3.2 Additive Piston Cost Model | Matt | 47 |

**Table of Contents**

**List of Figures**

**List of Tables**

## Abstract

Our project aims to compare the practicality and efficiency of additive manufacturing versus traditional manufacturing in select industries. Our report mainly focuses on the electronic and automotive manufacturing industries and includes a techno-economic assessment for each. These analyses are separated into two case studies. Our first case study is of printed circuit boards and our second is Porsche pistons. Each study focuses on a chosen part in one of the two industries, and includes life cycle analyses and cost analyses for both manufacturing methods during their typical operation. Our project aims to provide insight to both manufacturers and consumers by assessing and comparing both types of manufacturing.

## 1.0 Introduction

Manufacturing industries are the backbone of our economy. They take raw resources and process, prepare, and fabricate the different materials until the desired product is achieved. Manufacturing industries are divided among sectors, some of which include food, electronics, transportation, metals, plastics, and textiles. Oftentimes industries are interconnected and supply their finished products as intermediate products in other industries. Products can be made by either traditional or additive manufacturing. Traditional manufacturing, also sometimes called subtractive manufacturing, can take the form of a block of material fixed at a particular point, where small chips of the material are then removed over time to make the desired product. It can also take the form of a melted material that is then processed and cooled to retain a new shape. These processes differ from additive manufacturing, in which material is added over time to make the desired product.

Everything has an associated cost, which is an important factor to consider in manufacturing. To determine the most cost effective design and manufacturing method, it can be beneficial to utilize cost models. These models use formulas, equations or functions to measure and estimate the amount of time, effort, raw materials, and money used to create a product or deliver a service. Cost models can provide useful insight when it is not possible for detailed and exact costs to be outlined.

Every product or service also affects the environment in some way. A life cycle analysis is a method of measuring that impact over the course of a product's entire life cycle, starting with the resources used to manufacture each part up until the product's end of life. It takes into account environmental impacts such as energy, fuel, emissions, and waste products, and allows others to compare end products, production methods, and the materials used to create them. This information allows manufacturers to choose a design and manufacturing process most beneficial to them and the environment. The life cycle analysis is a crucial part of determining a product's overall carbon footprint. The software OpenLCA utilizes numerous databases to numerous categories of information on materials. It claims to be the world's leading software for life cycle assessment, and is free to use. We were able to use this program to find information regarding the environmental factors for different materials. This data was then used for our life cycle analyses in each case study.

` Our project aims to compare the practicality and efficiency of additive manufacturing versus traditional manufacturing in select industries. Our proposal will focus mainly on the electronic and automotive manufacturing industries and will include a techno-economic assessment for each. These analyses will take the form of a case study focused on life cycle analyses and cost analyses for a chosen part in those industries. Our aim is to provide insight by assessing and comparing both types of manufacturing during typical operation.

## 2.0 Background

Although essential, manufacturing has some disadvantages. High energy consumption, emissions from transportation and production, hazardous waste products, and a large carbon footprint are a few of the negative effects manufacturing has on the environment. The type of manufacturing method used and whether it was by traditional or additive means, influences the quality of product production and its resulting carbon footprint.

### 2.1 Traditional Manufacturing

The first manufacturing method we will discuss is the most common, traditional manufacturing. There are several standard processes that include: CNC machining, casting, forging, plastic forming, plastic joining, and injection molding. Typically, portions from a raw block of material are removed to create the end product or a cast is used to mold a molten material. Surface finishes can also be applied after the part is produced to add, alter, remove, or reshape the material. This can be very beneficial, as it can improve material strength and alter other properties, or be utilized to simply change the products aesthetic appearance.

In CNC machining, a material is secured to the machine while a numerically controlled tool travels along a computer generated path to remove material and create the part. This can be done by drilling, turning, or milling, and almost any material can be placed into the machine. CNC machining has a high tolerance to make very accurate parts, but it cannot create internal features or undercuts. Due to this fact, it is typically used for prototyping and for making engine and machine components.

Casting is a method of forming a part that involves pouring molten metal into a mold. For die casting or permanent mold casting, the mold is an inversion of the end product that is normally machined out of a block of steel. Other forms of casting, such as sand casting and investment casting, use an expendable, non reusable mold that is then destroyed after the part is made. Casting allows for finer internal structures when compared to machining, as the molten metal forms to the shape of the container it is in.

Forging involves taking a block of raw material and heating it below its melting point. The material becomes soft, and it is repetitively impacted with a large force until it forms the desired shape. Forging has the benefit of increased strength compared to machined and cast parts.

Plastic forming encompasses all methods of forming plastics such as thermoforming, pressure forming, and vacuum forming. In each, a sheet of plastic is heated and placed over a mold, where pressure or a vacuum force is applied to form the sheet into the desired shape. Only one side of the plastic can be fitted to the mold, as forming is a one sided process.

Plastic joining is between two semi-finished parts by welding, bonding, using adhesive, or fastening them together. The process used is dependent on the semi-finished part’s shape and how they were made. Plastic joining is a very time consuming process that can also be very costly in labor.

Injection molding involves softening a plastic material and injecting it into a mold. Once the plastic cools and solidifies, the piece is then ejected from the mold as a finished part. This process is typically used for plastic materials, but it can be used for others as well to create a high quality surface. Injection molding is primarily for manufacturing a large number of parts in a series, as the startup cost for injection molding is very high.

## 2.2 Additive Manufacturing

The other type of manufacturing process is additive manufacturing. It is a much more recently developed form of manufacturing, and is still evolving. Instead of using tools to remove material from stock or using force and temperature to change the shape of the raw material, additive manufacturing essentially starts from nothing and builds the part by adding small amounts of material in layers. Additive manufacturing can take form in a few different methods depending on the materials being used and the desired structure of the part.

The most common form of additive manufacturing is material extrusion of plastics such as PLA, ABS, Nylon, and PETG. This method is extremely prevalent in the recreational and small business section of the market due to the ease of use of the machines and low entry cost. These machines start off very basic and can scale greatly to include larger print sizes, increased speed, increased precision, and multiple different filaments for different colored parts as well as dissolvable supports.

Other methods of additive manufacturing include powder-bed fusion, direct energy deposition, sheet lamination, binder jetting, material jetting and vat photopolymerization. These methods can roughly be separated into four different types. Sheet lamination involves cutting individual layers and laying them on top of each other. This differs from direct energy deposition, material jetting, and material extrusion where the material that the part is made of is deposited onto the build tray. The final grouping includes powder-bed fusion, binder jetting, and vat polymerization, where the material is in a pool or tray in the form of a powder or liquid, and the material is selectively solidified using different methods such as binders and lasers (*Longborough University*).

Additive manufacturing is on the rise, and it has already found a foothold in certain elements of production such as rapid prototyping. Different fields are currently experimenting with AM technologies, some of which include 3D printed houses, organ creation, as well as electronics.

## 2.3 Electronic Industry

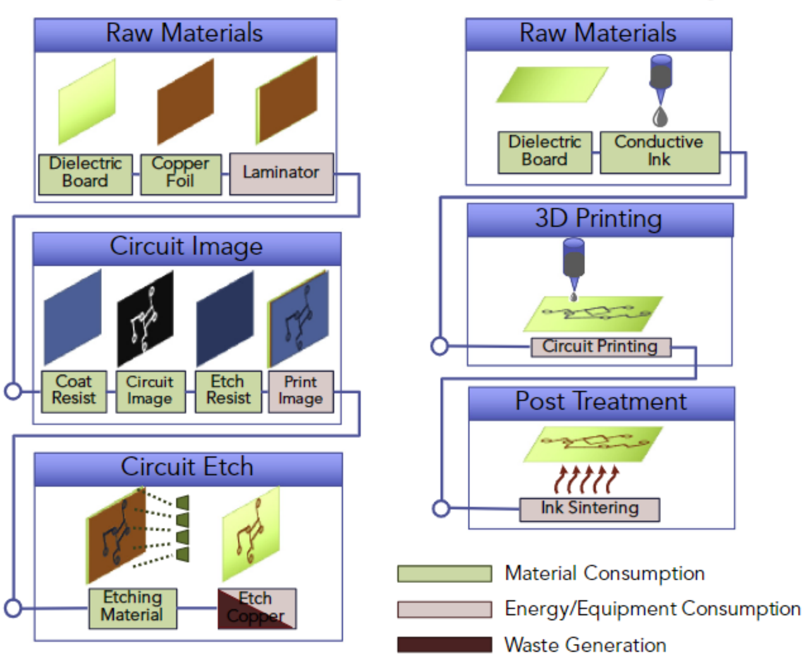
Our first industry of interest is the electronics industry, which one could argue is one of the most valuable industries to our modern society. Most products have an electronic component to them and as time goes on, devices and machines have gotten more complicated as technology has evolved. The electronics industry is constantly in high demand and rapidly changing. When the manufacturing of electronic components is interrupted, it can cause a domino effect of shortages of items and machines dependent on those components. This can vastly inflate prices and extend delivery times for all kinds of products. So how can one guarantee the smooth operation of the electronic industry to ensure the timely manufacturing of items in today's day and age?

For one, the additive manufacturing of electronic components is generally faster, more precise and more lightweight compared to traditional methods. It utilizes multi-material 3D printing to create products, typically with an electrically conductive material and isolating material. This simultaneous printing of both materials is the key to printing a functional electronic component. Additive manufacturing can also create complex geometries that were previously unattainable with traditional manufacturing and shorten the product’s developmental life cycle. However, the additive manufacturing of electronic components is costly and still a new technology. This factor can drive many companies away, preferring to stick to traditional manufacturing methods instead and make a greater profit *(xponentialworks.com)*.

Our first case study will analyze the manufacturing of a printed circuit board (PCB). These important little boards provide the mechanical support for a circuit as well as the electrical connections. PCBs are fabricated through batch processes and are custom made to order. We chose this part due to its importance in the electronic industry as the base for most electronic components, and because of the abundance of information online regarding its manufacturing process. Many articles speculate the best way to create them, whether by additive or traditional methods, however none provide case studies with tables or data to compare their performance. In our paper, we focused on exactly that.

Starting with the traditional manufacturing process of a printed circuit board, a dielectric substrate, typically glass reinforced epoxy, is laminated and both sides are bound by copper foil through a machining and lamination process. Resists are placed in a specific pattern to protect the material under it, where lithography then uses multiple chemicals to create the desired circuit patterns on the copper foil. Chemical etching then removes some of the copper to form circuit traces *(Dong, Y., Bao, C., & Kim, W. S., (2018))*. This process uses a large amount of energy and is very chemically intensive, using wet chemicals that can be harmful to the environment.

**Figure 1:** *Traditional vs Additive Manufacturing Methods: PCB*



*Note*. From left to right respectively, this image shows a simplified version of the traditional and additive manufacturing methods of a printed circuit board. Each manufacturing process can be broken down into three main steps *(Dong, Y., (2018))*.

The additive manufacturing process begins with a 3D model containing information about the object's surfaces. This information then undergoes a digital slicing procedure to create a successive sequence of 2D cross-sectional layers of the object. This code can be recognized and followed by a 3D printing platform to create the desired 3D object. For a printed circuit board, the dielectric substrate serves as a base, where circuit traces are then deposited as a reconstructed 2D layer *(Dong, Y., (2018))*. Nano Dimension, an additive manufacturing company focused on electronic components, recently utilized multi-layer PCB circuit manufacturing in order to reduce the time from creating a PCB design to creating a prototype. They were also able to create an additively manufactured integrated circuit with four layers in just 25 hours, and 16 of these boards in 100 hours *(Capabilities & Use Cases. Nano Dimension)*.

### 2.4 Automotive Industry

Our second industry of interest is automotive. Transportation is an essential aspect of modern life. It is needed to get to work, school, stores, or to see family and friends. The automotive industry has been growing and evolving rapidly since its inception around 120 years ago. One of the most important aspects of designing and manufacturing automobiles is the tight margins and focus on reducing costs at every opportunity. Additive manufacturing is being touted as an integral part of current and future aspects of the automotive industry. With its current abilities and attributes however, additive manufacturing is not being used for large scale production of parts or for the assembly of mass produced consumer products *(M, A., (2020))*.

**Figure 2:** *Excess Aluminum Powder in Piston Fabrication*

*Note.* The above image shows excess aluminum powder being removed from the finished parts by a vacuum. It is then filtered and cleaned so the aluminum powder can be reused *(M, A., (2020))*.

Many companies are experimenting with the world of additive manufacturing. One of those companies is Volkswagen with its many subsidiary brands such as Audi and Porsche. Porsche has begun 3D printing things such as seat pads in different comfort levels for select models, as well as high performance pistons for the highest trim of their famous 911 sports car. These pistons have been designed to include geometries that are far too complex for traditional manufacturing. The weight of the pistons can be reduced by up to 20% and allow for the introduction of complex internal structures such as a cooling duct to reduce operating temperatures, therefore increasing its efficiency *(Page, I., (2020))*. These gains might be fairly small, but every gram counts when working with both moving and rotating components as well as stationary structural components in high performance automobiles such as the Porsche 911 GT2 RS.

The traditional methods of manufacturing pistons included casting and forging. Pistons made by casting are typically cheaper and used for producing large quantities for less powerful commuter cars. Forged pistons are typically much stronger and used in performance vehicles such as the Porsche 911 GT2 RS as they can withstand the higher forces that are present in engines using forced induction to create more power *(Cars Direct (2012))*.

The newer method of producing the pistons with additive manufacturing begins with a 3D modeled part. This model is created using a method called topological optimization that automatically determines where unnecessary material should be added and can be removed based on the stresses that the part will undergo. This often results in a design that looks unnatural in the eyes of traditional manufacturing, but it can often look like something produced in nature. After the model is created, it is sent to a 3D printer that will then use lasers in a method called powder bed fusion to weld the aluminum powder together layer by layer. Porsche even uses a proprietary aluminum alloy for these pistons called M174+. The new production process, including the special aluminum alloy, creates a part that is 10% lighter, about half the theoretical max, and allows Porsche to squeeze 30 more horsepower from their engine *(Donut Media, (2021))*.

## 3.0 Methodology

Our project has two main objectives: to create cost models and life cycle analyses for both the additive and traditional manufacturing of our two case studies. By comparing the cost models and life cycle analyses between the different manufacturing methods, we hope to gain a better understanding of which is the most efficient, cost effective, and ecological for the selected part.

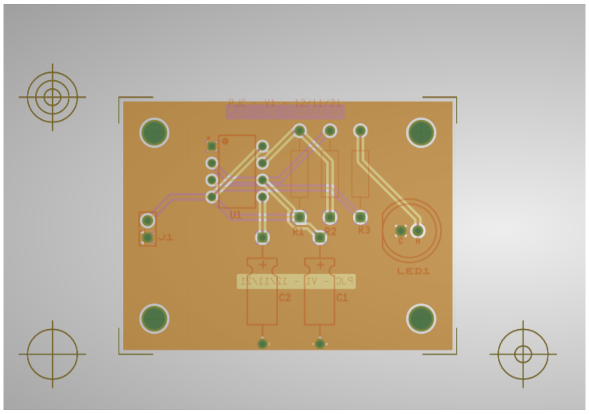
### 3.1 Case Study 1 Approach: PCBs

For the traditional manufacturing of a printed circuit board, we contacted ten different companies. Some of these included Millennium Circuits Limited, PS Electronics, Hopewell Companies, and Gorilla Circuits. Millennium circuits extensively described the manufacturing process on their website and stated that they can supply both small and large batches of printed circuit boards. Upon multiple tries to contact the ten traditional manufacturing companies, they either did not express interest in working with us on this project or did not have the information we desired. Due to this, our information relies heavily on the data provided publicly on their company websites along with stated assumptions. We used three different websites to obtain our traditional manufacturing quotes: JLCPCB, ALLPCB, and PS Electronics.

For additive manufacturing, we were only able to identify and contact two companies, Nano Dimension and Optomec. The company Nano Dimension is the leading manufacturer of industrial 3D printers for additively manufactured electronics (AMEs), whereas Optomec is solely a company that sells AME printers. Upon contacting Optomec, they stated that they could not provide data for the information that we sought, as they only sold AME printers and did not manufacture PCBs on site. After contacting the AME company Nano Dimension, they expressed interest in working with us and creating more ties with universities. We were able to correspond through emails and conduct a few online meetings to exchange information.

To begin collecting information, we then had to select a PCB design. Luckily, a colleague at WPI was working on a project that required creating a PCB model. After reaching out to him and explaining our project, he emailed files for us to use. It should be noted that this design was a draft and not a final version, as it was the only available design to us at the time we reached out. We used the website PCBway to view the gerber files and get the rendition. Figure 3 depicts the PCB board we will be using, and Table 1 displays its corresponding drilling information. Our model has the dimensions 38.1mm by 50.29mm by 1.6mm, and has two layers. The dimensions and other specifications associated with the PCB are listed in Table 2, which includes board type, the number of layers, the layer thickness, PCB size, base material, solder mask, silkscreen, and conductive material.

**Figure 3:** *Chosen PCB Model Rendition*



*Note.* This figure shows the layered image of our circuit board the website PCBway created using our gerber files.

**Table 1:** *Chosen PCB Drilling Information*

| Symbol | Size | Quantity | Plated | Slot Length |
|---|---|---|---|---|
| | 35.0000 | 11 | PTH | 0 (Round) |
| | 35.4331 | 10 | PTH | 0 (Round) |
| | 39.1700 | 1 | PTH | 0 (Round) |
| + | 125.0000 | 4 | PTH | 0 (Round) |

*Note.* This table shows the drilling information for our PCB, also from the website PCBway.

**Table 2:** *Chosen PCB Specifications*

| | | |
|---|---|---|
| **Board Type** | | Single board, Rigid |
| **Number of Layers** | | 2 |
| **Layer Thickness** | **mm** | 1.6 |
| **PCB Size** | **mm** | 38.1 x 50.29 |
| **Base Material** | | FR4 |
| **Solder Mask** | **oz** | Green, 1 oz |
| **Silkscreen** | | White |
| **Conductive material** | | LF-HASL |
| **Outer copper weight** | **oz** | 1 |

*Note.* This table includes the specifications associated with our chosen PCB model, which was then sent to companies for quotes.

### 3.1.1 PCB Cost Model

To gather data for our cost model, we took an activity based costing approach to create a direct link between design parameters and their impact on cost. The total cost of a traditionally manufactured PCB job order consists of the following cost elements: material costs, production costs, non-recurring tooling and programming costs, as well as yield costs. Material costs are driven by the amount of material added to or consumed by the product, and include chemicals used for stripping and etching, added materials such as copper plating, laminates and prepregs. The acquisition, storage and disposal costs associated with the materials are also considered. Production costs are driven by the time spent in each cost center and encompases all labor, overhead, and machining for each cost center. Non-recurring costs reflect the number and complexity of the tools required. It consists of one time costs such as creating the PCB design, programming the CNC machine, and programming the testing apparatus. The yield-loss costs consist of scrapping PCBs that fail inspection or tests, as well as ones that are shipped to the customer with defects (*Giachetti, R. E, & Arango, J., (2003)).* Table 1 below summarizes the factors for each process.

**Table 3:** *PCB Cost Centers*

| Fabrication Cost Centers | Major Cost Elements | Cost Drivers |
|---|---|---|
| Inner layer processing | Material cost | Number of inner layers<br>Number of panels<br>Copper weight |
| | Production costs | Number of inner layers<br>Copper weight<br>Number of panels |
| AOI | Yield-loss costs | Inner line circuit length |
| Inner layer laminating | Material costs | Number of layers |
| | Production costs | Number of panels |
| Drilling | Production costs | Number of holes<br>Board thickness<br>Number of panels |
| | Yield-loss costs | Number of holes<br>Hole diameter |
| Outer layer processing | Material costs | Board areas<br>Copper weight<br>Number of panels |
| | Production costs | Copper weight<br>Number of panels |
| Soldermask | Material costs | Soldermask type<br>Number of sides to mask |
| HASL | Production costs | HASL required? |
| Electrical Test (flying probe only) | Production costs | Number of networks<br>Single/double sided? |
| Electrical test (bed of nails only) | Non-recurring tooling costs | Number of test points |
| | Production costs | Number of SMT test points |
| Electrical test | | Single or double sided? |
| | Yield-loss costs | Outer line width<br>Outer line circuit length<br>Soldermask tolerance<br>Annular ring size |
| | Programming costs | Number of test points |

*Note*. This table shows cost centers, their cost elements, and the associated cost drivers for a traditionally manufactured printed circuit board. The table was modeled after an article that described an activity based approach to cost modeling for PCB fabrication (*Giachetti, R. E, & Arango, J., (2003)).*

We utilized the websites JLCPCB, ALLPCB, and PS Electronics to give us quotes regarding the different quantities of printed circuit boards. We sent the previously described information, the PCB gerber files and the model specifications in Table 2, to the different websites along with the chosen quantities of 10, 50, 100, and 1,000 PCBs. We received four quotes from each source in return. This allowed us to obtain a broader scope of the total manufacturing cost while also being able to determine which is the most accurate source. By choosing a range of quantities, this allowed us to estimate an ethical quantity of PCBs.

The next cost center involves the cost of electricity. We were able to estimate the cost of electricity for the different quantities by using the National Grid energy rates in Massachusetts for early 2022. By multiplying the rates by the kilo-Watt-hours it took to manufacture the different quantities for both manufacturing methods, we were able to estimate their total electricity costs. A table was then created to display the electrical data.

Next, we created a section for the cost model comparison. It includes the total costs for a traditional manufacturing company and an additive company, and details the quantity, manufacturing time, total manufacturing cost, and estimated electricity costs. By using this table, we were able to make observations regarding the costs for the two manufacturing styles and their ramifications.

### 3.1.2 PCB Life Cycle Analysis

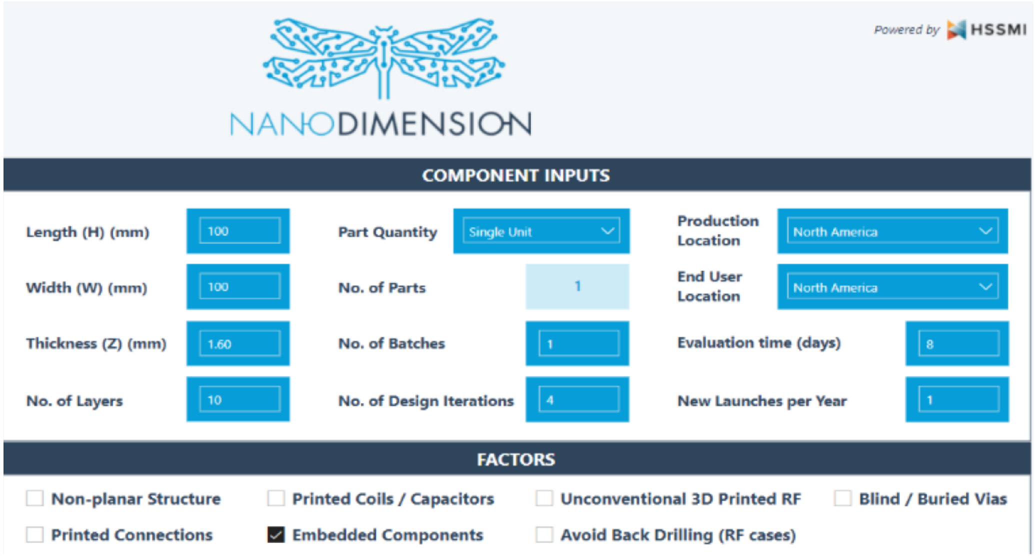
To reiterate, a product's life cycle analysis begins at the resources used to manufacture each part and stretches to the product's end of life. It measures factors such as the amount of product produced, the energy consumed, chemical used, waste products, and emissions. Different factors can affect the lifespan of a part or product, such as PCB’s being influenced by their type, size, number of layers, temperature, and environmental factors.

The lack of specific information for the traditional manufacturing of our PCB model extends to our life cycle analysis as well. We were unable to receive life cycle amounts on our PCB design through traditional means, as we used online websites that do not provide this feature. Without knowing the amounts of materials going into the manufacturing process and the amount contained in the product, it is impossible to compute the amounts of material recycled, material wasted, any contamination, or emissions. With numbers, we would have utilized OpenLCA and its numerous databases to find information on the materials regarding their environmental factors. Our colleagues in the Energy Metals Research Group at WPI created a spreadsheet of calculations for their research on iron powder flow electrolysis (Wang, Y., (n.d.)). This spreadsheet would have been utilized to calculate total emissions, energy balance, manufacturing flow of materials, and an uncertainty analysis for our two case studies. Our aim would have been to assess the PCBs cradle to gate life cycle, from the moment the resources are extracted to when it gets to the factory gate, or its cradle to grave cycle, from the moment the resources are extracted to when the product is disposed of.

Although we were unable to receive life cycle data for traditional manufacturing, we were able to find a previous paper regarding the life cycle of a PCB that included an inputs and outputs table. Since we were unable to communicate with local companies, we will be using this table based on a PCB plant in Turkey for our life cycle analysis. We do so with the knowledge that the PCB they used may very likely have been a different size, affecting the values in their chart and subsequently our comparisons and conclusions.

For our additive life cycle, we were unable to receive specific input and output numbers for our chosen PCB model. Instead, we received a PDF file from Nano Dimension employees containing a life cycle analysis of their DragonFly IV printer compared to conventional manufacturing methods. If we had received specific values for our model, there would have been an error of analysis due to the input and output values for traditional being for a different PCB design in a different country four years prior. The data from the analysis Nano Dimension conducted would be more reputable since their comparisons were conducted in the same year and with the same criteria. It should also be noted that the PDF file seems to detail the PCBs gate to gate life cycle, which is the timeframe of when the product enters the factory to when it exits the factory. Figure 4 below shows the PCB data they used to calculate their life cycle analysis.

**Figure 4:** *Nano Dimension's PCB Specifics for their Life Cycle Analysis*



COMPONENT INPUTS

| | | | | | |
|---|---|---|---|---|---|
| Length (H) (mm) | 100 | Part Quantity | Single Unit | Production Location | North America |
| Width (W) (mm) | 100 | No. of Parts | 1 | End User Location | North America |
| Thickness (Z) (mm) | 1.60 | No. of Batches | 1 | Evaluation time (days) | 8 |
| No. of Layers | 10 | No. of Design Iterations | 4 | New Launches per Year | 1 |

FACTORS

☐ Non-planar Structure
☐ Printed Connections
☐ Printed Coils / Capacitors
☑ Embedded Components
☐ Unconventional 3D Printed RF
☐ Avoid Back Drilling (RF cases)
☐ Blind / Buried Vias

*Note.* This figure outlines the PCB specifics Nano Dimension used to calculate their life cycle analysis. Nano Dimension employees shared this figure with us through a PDF file detailing the ecological impact of the DragonFly IV printer.

Nano Dimension partnered with Fuss & O'Neill and HSSMI with the aim to confirm ecological data. Fuss & O'Neill were able to conduct an industry wide analysis of electronics manufacturing for comparable manufacturing data. HSSMI is a global sustainable manufacturing consultancy and they are experts in the circular economy. They consolidated Fuss & O'Neill's data while also conducting an extensive industry analysis. HSSMI created a tool to generate accurate ecological outputs between alternate manufacturers and the DragonFly IV printer. They used the above specifications in Figure 4 and created bar graphs with the generated data to compare manufacturing technologies. These graphs can be found in our resulting PCB life cycle analysis.

### 3.2 Case Study 2 Approach: Piston

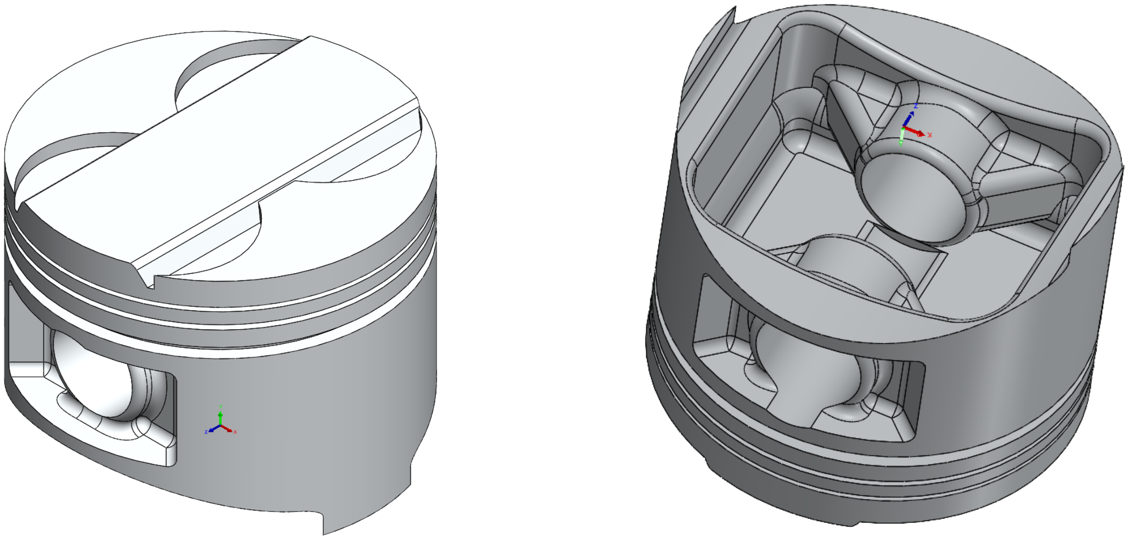
For the traditional manufacturing of automotive pistons, we contacted a faculty member at WPI who discussed the capabilities that WPI has for casting aluminum parts. The casting done on campus is solely for research purposes, so it is extremely low volume and inefficient. This would not be an acceptable avenue for a company to pursue when producing their parts, but we will include it briefly to show a starting point. We also contacted six different companies that cast aluminum parts for customers. These companies included Olson Aluminum Casting, Mystic Valley Foundry, and Modern Aluminum. We heard back from half of the casting companies and two of them were willing to work with us. They were able to give us more information on their process as well as an estimate for pricing of their services. The other companies either did not respond or were unable to help us with the information we needed.

For the additive manufacturing of the pistons, we once again reached out to faculty on campus to find out more information before contacting multiple companies. To reiterate, the capabilities of WPI would not meet industry demands for more than a basic prototyping capability as they only have a single machine that is only able to produce a single piston approximately every 36 hours. With this in mind, we will use this as an example starting point.

The companies we contacted for information include Xometry, Craftcloud, and DMLS. None of these companies were able to provide us with information, so we worked with what was publicly available through their websites. All of the additive manufacturing companies offer AlSi10Mg alloy in their material lists, so that will be used as a control variable between all the companies.

To effectively compare the two processes, we had to establish a model that would be used for both in order to reduce the number of uncontrolled variables. The model was based on a piston from the high performance honda engine from the late 80s through the early 2000s as part of the B series engines. This engine powered cars such as the Civic SiR, Del Sol, and Integra Type R. An image of the model used is shown below.

**Figure 5:** *Piston Model*



*Note.* This figure shows the piston model that was used to compare the two processes.

The piston model used for this project is to be made of aluminum-silicon-magnesium or similar alloy through both additive and traditional manufacturing. The piston measures approximately 81mm in diameter and 63mm in height and weighs in at 411g with a volume of $153cm^3$.

### 3.2.1 Piston Cost Model

In order to gather the data needed to make the comparison between additive and traditional manufacturing, we took the same activity based method to see how the different aspects of each method affect the price of each part. The most important aspects to each method are the material cost, setup cost, and operating cost. The material cost for this part consists exclusively of the cost of the aluminum used to make the parts. The materials used to create the part from additive manufacturing is solely the Aluminum alloy powder that the printers use, and the materials used in casting are ingots of Aluminum alloy that will be melted down and poured into the cast. The setup costs differ between additive and traditional manufacturing. For additive manufacturing, it includes any programming that needs to be done to setup the code that the machine uses to turn a 3D model into a physical part. For traditional manufacturing, this cost consists of machining a mold to use for sand casting or die casting. The operating costs consist of the electricity cost for running the machines and plant as well as any other expenses that occur during the process of creating the part.

In order to gather the data for the cost models of both methods we reached out to several companies as well as used the websites of others to provide quotes. We used the websites Fathom, Craftcloud, Stratasys, and Protolabs to give us quotes for each of the different quantities of pistons created using additive manufacturing. We provided the 3D model shown in Figure 5, and we set the different manufacturing options to the closest options available at each different company surrounding the printing method, powder used, resolution, and finish type. For Traditional manufacturing, we emailed several companies to gather information and obtain quotes. Only two companies responded and were willing to work with us. These companies were Marlborough Foundries in Marlborough, MA and Olson Aluminum in Rockford, IL.

Similarly to PCB's, we established an electricity cost estimate table to go along with each manufacturing method. We estimated the amount of electricity that would be required to produce each quantity of pistons for each manufacturing method, and we multiplied that by the kWh rates for Massachusetts in 2022. This gives us an estimate of the electric cost if the parts were to be manufactured in Massachusetts.

Next, a comparison was made between the two cost models that includes the quantities produced, the price given from the quotes, the lead time, and the estimated electric cost. By creating this table, we are better able to compare each method at different quantities in terms of the price and length of time required as time and money are often the two most important factors when choosing how to source a part.

### 3.2.2 Piston Life Cycle Analysis

Pistons are made using several different methods including 3D printing and casting. These methods affect the life cycle analysis of the product being made in different ways. The life cycle of a part begins with raw resources and ends when the product is thrown away, recycled, or in some other way ceases to be used anymore. Different factors in the product can affect the energy and materials used at different stages of the products life cycle. For example, additive manufacturing uses a powdered aluminum alloy compared to ingots of aluminum alloy used in casting. In order to create this powder, the aluminum goes through an additional step that therefore increases the energy consumed in the pre-production steps of additive manufacturing.

Additive manufacturing can make up for this increased energy need by creating a part that uses less material through its inherent ability to make more complex parts with hollow internal structures. Through making a lighter part, the amount of gasoline that must be consumed in an internal combustion to produce the same power is less than that of a traditionally manufactured piston as the combustion needs to move less mass to push the piston away and spin the crankshaft.

Unfortunately, we were unable to attain the proper level of information during the course of this project to properly assess the entire life cycle of the pistons in both traditional and additive manufacturing.. Due to this, our project has been limited to the section of the part's life that occurs during production. We were able to gather some useful data on this from the information gathered from the company emails and websites as well as a study done on die casting in 2003. The study was conducted at a facility that was most likely producing a completely different part in a completely different quantity and at a less efficient rate than today, so it will be used as an estimate.

## 4.0 Results and Analyses

This section presents data acquired primarily from company websites and previous papers, as well as from companies directly when applicable. Missing information was estimated through our own calculations and compiled into excel spreadsheets for better comprehension and clarity. We then created cost analyses and life cycle analyses and organized the information into tables. These analyses resulted in findings that will hopefully inform and aid others in choosing the best manufacturing process for PCB or engine piston fabrication.

### 4.1 Resulting PCB Cost Models

For our PCB case study, the information we gathered was split into a traditional manufacturing cost model, an additive manufacturing model, and a comparison section to analyze the two cost models side by side. We believed this would be the most effective way to display and compare the collected data due to its extensive size. The following sections display the steps we took to create these analyses in full detail along with their results.

#### 4.1.1 Traditional PCB Cost Model

By utilizing the websites JLCPCB, ALLPCB, and PS Electronics, we submitted our PCB gerber files from our methodology section (shown previously in Figure 3) and model information (listed previously in Table 1 and Table 2), along with our four chosen quantities of PCBs. We received four quotes from each source, with some websites giving a more in-depth cost breakdown than others. Table 4, Table 5, and Table 6 below display the received quotes from JLCPCB, ALLPCB, and PS Electronics respectively.

**Table 4:** *JLCPCB Quote*

| **Quantity** | **# of PCB's** | 10 | 50 | 100 | 1,000 |
|---|---|---|---|---|---|
| **Manufacture time** | **days** | 2-3 days | 5-6 days | 5-6 days | 5-6 days |
| **Shipping time** | **days** | 2-5 business days | 2-5 business days | 2-5 business days | 2-5 business days |
| **Weight** | **kg** | 0.006 | 0.32 | 0.64 | 6.63 |
| **Board Price** | **$** | $0.00 | $5.90 | $11.80 | $117.70 |
| **Film Price** | **$** | $0.00 | $0.60 | $0.60 | $0.60 |
| **Engineering fee** | **$** | $5.00 | $9.00 | $9.00 | $9.00 |
| **Surface finish** | **$** | $1.20 | $5.20 | $5.20 | $5.20 |
| **Shipping price** | **$** | $19.11 | $22.16 | $25 | $131.83 |
| **Total Price** | **$** | $25.31 | $42.86 | $51.81 | $264.33 |

*Note*. This table displays the information received from the website JLCPCB regarding the PCB files and specifications we sent them (*PCB Prototype & PCB Fabrication Manufacturer—JLCPCB*).

**Table 5:** *ALLPCB Quote*

| **Quantity** | **# of PCB's** | 10 | 50 | 100 | 1,000 |
|---|---|---|---|---|---|
| **Manufacture time** | **days** | 2 day lead time | 2 day lead time | 2 day lead time | 2 day lead time |
| **Quote Price** | **$** | $31 | $17 | $24 | $152 |

*Note*. This table displays the information received from the website ALLPCB regarding the PCB files and specifications we sent them (*Instant PCB Quote Online—PCB Cost Calculator).*

**Table 6:** *PS Electronics Quote*

| **Quantity** | **# of PCB's** | 10 | 50 | 100 | 1,000 |
|---|---|---|---|---|---|
| **Manufacture time** | **days** | 9 day lead time | 9 day lead time | 9 day lead time | 9 day lead time |
| **Unit Price** | **$/PCB** | $2.000 | $0.400 | $0.205 | $0.205 |
| **Set up and Electronic Test** | **$** | $100.00 | $100.00 | $100.00 | $100.00 |
| **Total Price** | **$** | $120.000 | $120.000 | $120.432 | $304.318 |

*Note*. This table displays the information received from the website PS Electronics regarding the PCB files and specifications we sent them (*PS Electronics*).

By comparing data received from the three sources, it is apparent that JLCPCB has a more in-depth cost breakdown whereas ALLPCB is lacking in this regard. PS Electronics is in between the two, being only slightly more detailed than ALLPCB, and yet still not as detailed as JLCPCB. When it comes to manufacturing and shipping times, JLCPCB seems to be the most reliable source, as the times grow slightly larger as the quantities increase. For these reasons listed, the data from JLCPCB will be used in our PCB cost model comparison.

A previous paper regarding a PCB traditional manufacturing plant estimated that in order to fabricate one PCB, 7.135kW of energy is required (*Giachetti, R. E, & Arango, J., (2003)).* If the manufacturing was conducted in Massachusetts, where the average commercial electricity rate was 17.6¢ per kW in early 2022, we can estimate the cost of energy for the different quantities of printed circuit boards (*Energy Bot*, (2022)). Table 7 below shows the calculated energy costs for traditional manufacturing for different quantities of PCB’s.

**Table 7:** *Cost of Electricity Through Traditional Means*

| **# of PCBs** | 1 | 10 | 50 | 100 | 1,000 |
|---|---|---|---|---|---|
| **Energy used in kWh** | 7.135 | 71.350 | 356.750 | 713.500 | 7135.000 |
| **Estimated electricity cost** | $1.256 | $12.558 | $62.788 | $125.576 | $1,255.760 |

*Note*. This table shows the estimated price of electricity in Massachusetts for the different quantities of traditionally manufactured printed circuit boards.

### 4.1.2 Additive PCB Cost Model

As we were only able to successfully contact one additive manufacturing company, Nano Dimension, the information we have may not be representative of the AME industry as a whole. Information was gathered from public information on their companies website as well as through communication with Nano Dimension employees.

Nano Dimension offers three different services on their website for PCB fabrication. The first is called an “AME Test Ride,” and allows you to get your design 3D printed and shipped worldwide. With this service you are able to speak with an expert, upload your gerber files, do a design check, and then print and ship your design. The cost for this service is listed as US $1,000. The second service is called “AME Co-Design,” and allows you to work with their team to realize your 3D electronic design idea together. With this service you are able to do the same as the previous service with the added benefits of discussing your idea with an application engineer, working with their design experts to create a 3D AME design, component assembly, and testing. The cost for this service is US $3,000-5,000. The third service is called “Advanced AME Project,” and allows you to co-develop a special AME application with a short run production using their engineers. With this service you are able to speak with an expert, discuss your challenges and ideas with their application engineers, define your project scope and interaction, receive design concepts, print samples, component assembly, testing, and shipping. The cost for this service is US $5,000-10,000 (*NaNoS Shop. (n.d.)).* No other information was given regarding a production or shipping time frame without first purchasing the service.

After having an online meeting with representatives from Nano Dimension, they were able to give us a quote using our PCB files. With our PCB's size, they informed us that they would be able to fabricate 8 in a batch in their DragonFly IV printer. This brought the cost for printer set-up to $800 and the creation of a batch to $1,400. This information can be seen below in Table 8, with the associated cost per board. Since it was the easiest to group the boards in batches of 8, we received quotes in multiples of 8 that were as close to our chosen quantities as possible. The total manufacture time was calculated with the knowledge that set-up would take an hour and our batches of 8 would take 6 hours each. The total time was then converted from hours to days.

**Table 8:** *Nano Dimension Quote*

| **Quantity** | **# of PCB's** | **8** | **48** | **96** | **1000** |
|---|---|---|---|---|---|
| **Quantity** | **# of batches of 8** | **1** | **6** | **12** | **125** |
| **Manufacture time** | **days** | 0.29 days | 1.54 days | 3.04 days | 31.29 days |
| **Shipping time** | **days** | Can be in-person | Can be in-person | Can be in-person | Can be in-person |
| **Associated cost per board** | **$/board** | $275.00 | $191.67 | $183.33 | $175.80 |
| **Shipping price** | **$** | $75 | $75 | $75 | $75 |
| **Total cost** | **$** | $2,275.00 | $9,275.16 | $17,674.68 | $175,875.00 |

*Note*. This table displays the information received from the AME company Nano Dimension regarding the PCB files and specifications we sent them. The quantities are different from our traditional manufacturing quotes, since they'd be printing in batches of 8.

The brochure for the 3D electronic DragonFly IV printer at Nano Dimension mentions that it requires 20 amps through an uninterrupted power supply, which corresponds to about 2kW. With our previously calculated manufacturing times and the same 17.6¢/kW rate used previously for electricity in Massachusetts, it is possible to estimate the cost of electricity for the different quantities. Table 9 below calculates the price of electricity for the additive manufacturing of different quantities of PCB's.

**Table 9:** *Cost of Electricity Through Additive Means*

| **# of PCBs** | 8 | 48 | 96 | 1,000 |
|---|---|---|---|---|
| **Approximate Hours** | 7 | 37 | 73 | 751 |
| **Energy used in kWh** | 14 | 74 | 146 | 1502 |
| **Estimated electricity cost** | $2.521 | $13.327 | $26.295 | $270.510 |

*Note*. This table calculates the estimated price of electricity in Massachusetts for the additive manufacturing of printed circuit boards.

### 4.1.3 PCB Cost Model Comparison

To best compare the cost information between the two manufacturing styles, relevant data was compiled into Table 10 below. There we can see the quantities, manufacturing times, total manufacturing cost, and the estimated electricity cost for JLCPCB and Nano Dimension.

**Table 10:** *Cost Comparison Between JLC PCB and Nano Dimension*

| **Traditional Manufacturing: JLC PCB** | | | | | |
|---|---|---|---|---|---|
| **Quantity** | **# of PCB's** | 10 | 50 | 100 | 1,000 |
| **Manufacture time** | **days** | 2-3 days | 5-6 days | 5-6 days | 5-6 days |
| **Total manufacturing cost** | **$** | $25.31 | $42.86 | $51.81 | $264.33 |
| **Estimated electricity cost** | **$/kWh** | $12.558 | $62.788 | $125.576 | $1,255.760 |
| **Additive Manufacturing: Nano Dimension** | | | | | |
| **Quantity** | **# of PCB's** | **8** | **48** | **96** | **1000** |
| **Manufacture time** | **days** | 0.29 days | 1.54 days | 3.04 days | 31.29 days |
| **Total manufacturing price** | **$** | $2,200.00 | $9,200.16 | $17,599.68 | $175,800.00 |
| **Estimated electricity cost** | **$/kWh** | $2.521 | $13.327 | $26.295 | $270.510 |

*Note*. This table was created using the traditional company JLCPCB’s quote and electricity estimation as well as the additive company Nano Dimension’s quote and electricity estimation for easier comparison.

After looking at the table, it is abundantly clear that for a single layer, simple design PCB, traditional manufacturing is more cost effective. The additive manufacturing of PCBs uses less energy and therefore pays less in electricity usage, however their manufacturing price is so much higher that there is almost no competition when it comes to cost. The traditional manufacturing of PCBs is cheaper, even when electricity and other factors are added to the total cost.

### 4.2 Resulting PCB Life Cycle Analyses

For traditional manufacturing methods, Table 11 below depicts traditional PCB manufacturing inputs and outputs during its life cycle. This information was based on a previous research paper about the life cycle assessment of a PCB manufacturing plant in Turkey *(Ozkan, E., Elginoz, N., & Germirli Babuna, F., (2017))*. We were unable to replicate this table with information regarding a printed circuit board manufacturing plant in the United States, and were also unable to find a similar article with more recent data. Due to this, we will use their values for the inputs and outputs when manufacturing a single printed circuit board, with the knowledge that these values have most likely changed over time and will be slightly different.

**Table 11:** *PCB Traditional Manufacturing Inputs and Outputs*

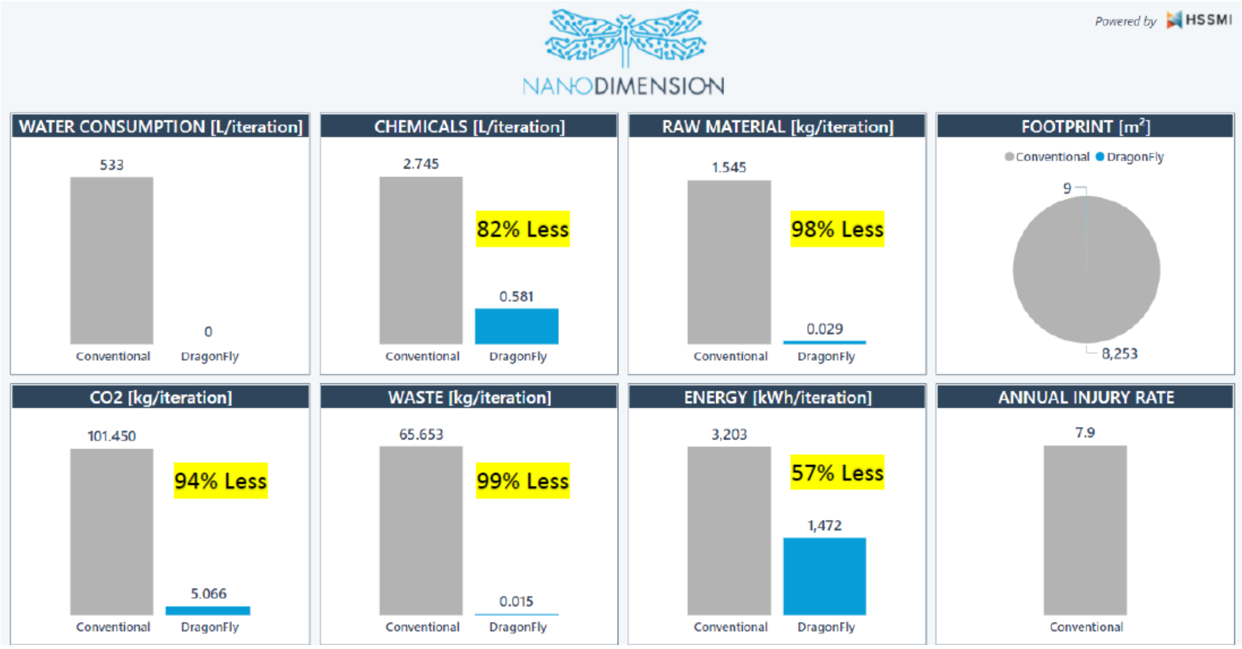
| **Inputs** | | | **Outputs** | | |
|---|---|---|---|---|---|
| **Materials** | **Amount** | **Unit** | **Materials** | **Amount** | **Unit** |
| **Fabrication of Board** | | | **Product** | | |
| Glass fiber woven | 1.596 | kg | PCB | 1 | m^2 |
| Copper | 0.615 | kg | **Product** | | |
| Epoxy resin | 0.31 | kg | Textile waste (contaminated) | 0.019 | kg |
| Water (fabrication) | 0.407 | m^3 | Plastic waste (contaminated) | 0.004 | kg |
| **Manufacturing of PCB** | | | Metal waste (contaminated) | 0.009 | kg |
| Water (fabrication) | 0.058 | m^3 | Board waste (hazardous and non-hazardous) | 0.094 | kg |
| Solvents | 0.069 | kg | Wastewater | 0.465 | m^3 |
| Etching agent | 1.89 | kg | Copper | 0.27 | kg |
| Etching resist ink | 0.011 | kg | Copper (recovery in the factory) | 0.091 | kg |
| NaOH | 0.008 | kg | Solder slag | 0.003 | kg |
| Solder mask | 0.051 | kg | **Emissions** | | |
| Solder bar | 0.004 | kg | TOC (propane) | 2.83x10^-3 | kg |
| Flux | 0.014 | L | Dust | 4.9x10^-5 | kg |
| Energy | 7.135 | kWh | Ag | 5.47x10^-6 | kg |
| | | | Cu | 5.47x10^-6 | kg |

*Note*. This table shows the input and output data of traditional PCB manufacturing found from an article on the life cycle assessment of a PCB plant in Turkey *(Ozkan, E., Elginoz, N., & Germirli Babuna, F., (2017))*.

It is worth noting the amounts of solvents and etching agents put into the manufacturing process as well as the amounts of harmful byproducts, waste, and emissions created as a result of manufacturing only one PCB. Although relatively small with emission values ranging from milligrams to grams, when you multiply these values to account for the quantity of PCB's in an order and then by hundreds of orders a company produces, they become very prominent.

For additive manufacturing methods, no water or acids are used and no etching or lithography is performed. "The DragonFly IV Combines over 70 steps into one complete process, optimizes material use, drastically cuts environmental impacts, and requires minimal relative energy use," (*Nano Dimension*, 2022) They do use solvents and have to clean the printheads to ensure they are at peak performance, but it contains 82% less chemicals than its traditional counterpart, and resulting $CO_2$ emissions are 94% less. The exact chemicals present in the solvents were not mentioned. The DragonFly IV printer has two printheads that deposit ink. One uses dielectric ink, specifically polymer based ink for insulation and structure, and the other uses silver nanoparticle ink to print conductive features. This allows them to use 98% less raw materials than conventional methods of manufacturing and produce 99% less waste. Energy use in additive manufacturing is also reduced, using 57% less than traditional manufacturing. When it comes to taking up space, additive takes up about 9 $m^2$ while conventional methods take up 8,253 $m^2$. It is also worth noting that there is an average annual injury rate of 7.9 in traditional manufacturing compared to 0 injuries due to additive manufacturing. Nano Dimension's DragonFly IV printer has an interlocking mechanism that prevents anyone from opening the door when a print job is underway. These numbers can be seen below in Figure 6, which was created by Nano Dimension to assess their environmental impact. It should be noted that their life cycle analysis seems to be for the gate to gate life cycle of a printed circuit board, and only assesses the data of the board's time in the factory. Their data does not seem to include upstream processes in a cradle to gate life cycle analysis, such as the materials and other inputs used to create both of their inks, or post processes in a cradle to grave life cycle, such as transportation, use, and end of life.

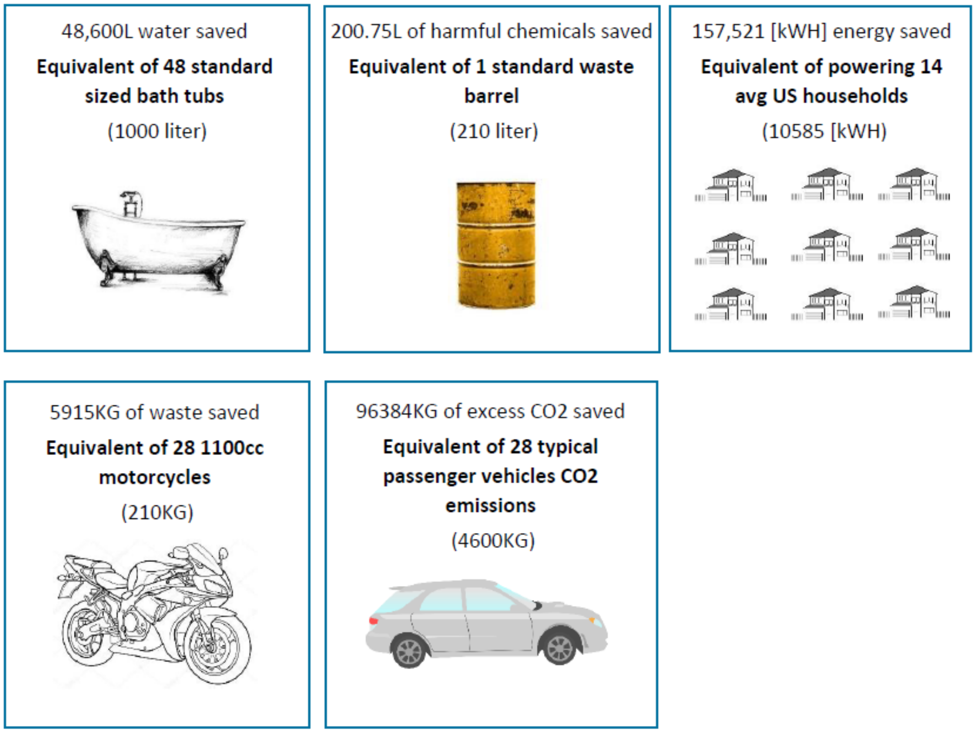
**Figure 6:** *Life Cycle Analysis conducted by Nano Dimension*



*Note*. This figure came from the PDF file sent by Nano Dimension employees. It is the result of their impact analysis of the DragonFly IV printer compared to traditional manufacturing methods. It seems to detail the gate to gate life cycle for PCB manufacturing.

When analyzing Figure 6 above, it is clear that the additive manufacturing of PCBs is more environmentally friendly. With every statistics over 50% better than conventional manufacturing methods and most above 80%, there is no disputing that fact. Nano Dimention's analysis also extends to potential savings over the period of a year, which you can see in Figure 7 below.

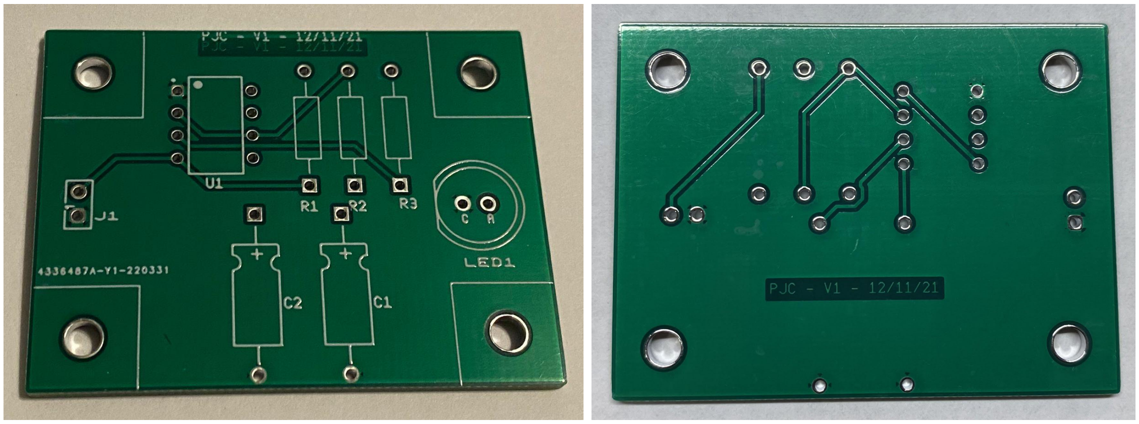
**Figure 7:** *Potential Savings by using Additive Manufacturing*



*Note*. This figure was included in the PDF file Nano Dimension employees shared with us. By using the previous Figure 6 data, they estimated potential savings by using additive manufacturing to fabricate PCB's instead of conventional methods.

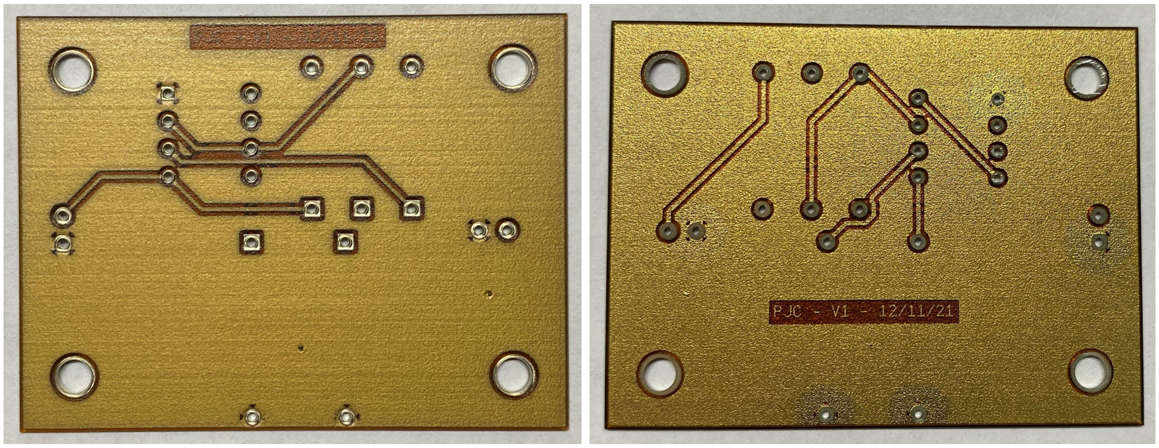
We were able to purchase circuit boards from both our traditional manufacturing company of interest, JLCPCB, and our additive one, Nano Dimension. We sent the same files and PCB information detailed in our report to both companies. The figures below show the two resulting circuit boards.

**Figure 8:** *Our PCB design manufactured by JLCPCB*



*Note*. This figure depicts the circuit board that was manufactured by the company JLCPCB. The left image is of the top of the PCB while the right image is of the bottom.

**Figure 9:** *Our PCB design manufactured by Nano Dimension*



*Note.* The above figure depicts our circuit board design as manufactured and shipped by the company Nano Dimension. The left image is of the top of the PCB while the right image is of the bottom.

After receiving the two PCB's, their differences were very apparent. The additive board did not include any of the board identifiers seen in our model rendition in Figure 3, such as the labeling for resistors and capacitors. The traditional PCB was also much thicker and heavier, where the additive one was two and a half times smaller in thickness and only a fraction of its weight. The traditional PCB has a glossy, smooth texture on both sides, whereas only the bottom of the additive board is smooth and glossy. The front of that board has a similar texture to smooth plastic. The edges of the traditional board are very slightly rounded, and the edges of the additive one have a much sharper edge. The traces on the boards are almost identical, except for the traditional board tracing being slightly raised. The PCB model we sent was an unfinished one, so we unfortunately have no way of testing that both circuit boards work.

The capability of the additively manufactured boards to be much thinner and lighter can be beneficial to many products. Companies have recently been switching to more eco-friendly product production or plan to in the near future. That being said, it is highly likely that there will be a switch, even if it is a partial one, to additive manufacturing for the fabrication of printed circuit boards and possibly other electronics.

### 4.3 Resulting Piston Cost Model

Similarly to the PCB section, the piston case study will be split into three sections containing the traditional manufacturing cost model, additive manufacturing cost model, and a comparison of the two cost models.This format will help display the information gathered about each method and show how they compare to each other. These next three sections will similarly show the steps taken and the results that we achieved from our research.

### 4.3.1 Traditional Piston Cost Model

We reached out to multiple casting companies in search of information regarding the cost to cast an aluminum piston in various different quantities. Only two of the companies responded to our requests and both companies were unable to provide us with the information we were looking for due to the fact that they were not interested in going into that level of detail with someone who was not looking to purchase the parts. We were able to gather a small amount of information from one of the engineers we talked to as well as the casting facilities on campus. Using the information gathered from these two sources, we will be able to make an estimate as to the time and cost that would go into casting aluminum pistons.

The biggest cost associated with die casting is the cost to create the mold for the part. In our conversation with an engineer at a casting company, he estimated that a die mold for our control part was estimated to cost somewhere in the range of $50,000. Fortunately the mold would be good for hundreds of thousands of parts, so this would be a single time cost and would last for the duration of essentially any amount of parts we would want to cast.

One of the most important costs of casting with aluminum is the price of the aluminum being used to cast the part. At the time of writing this paper, the price of aluminum was approximately $2,500/metric ton. At a weight of 0.411kg, each piston will use about $1.03 worth of aluminum.

The third major component of the cost to produce the pistons is the cost to operate the facilities. According to the study done by the members of the Ohio State University, the operating energy consumption of one of the die casting plants surveyed sold 55,078,546 pounds of casts per year and had a total energy usage of 3,744 BTU/lb which equates to about 1.1 kWh of energy used to create 1kg (2.2lb) of aluminum castings (Brevick, et. al). This equates to 0.21 kWh of energy used to produce each piston.

**Table 12:** *Cost Estimates for Traditional Manufacturing*

| **# of Pistons** | 1 | 4 | 20 | 80 | 400 |
|---|---|---|---|---|---|
| **Die Cast Mold Cost** | $50,000 | $50,000 | $50,000 | $50,000 | $50,000 |
| **Mold Cost per Piston** | $50,000 | $12,500 | $2,500 | $625 | $125 |
| **Amount of Aluminum Used in kg** | 0.411 | 1.644 | 8.22 | 32.88 | 164.4 |
| **Estimated Material Cost** | $1.03 | $4.12 | $20.06 | $82.4 | $412 |
| **Energy Used in kWh** | 0.21 | 0.82 | 4.1 | 16.4 | 82.2 |
| **Estimated Electricity Cost** | $0.04 | $0.15 | $0.74 | $2.96 | $14.78 |
| **Total Cost per part** | $50,001 | $12,501 | $2,501 | $626 | $126 |

*Note*. This table displays the values estimated for the energy consumption and cost to produce aluminum cast pistons using a die cast process.

A disadvantage of die casting is the high initial cost and time between submitting a model and receiving a part. The mold for a die cast is machined from tool steel and can take up to a month to make after submission of the part mode (*FAQs about aluminium extrusion, 2022*). In addition to this time, the facility must do other preparations and actually cast the product. With this accounted for, it can be anywhere between 45-60 days between submitting your order and receiving your parts.

Through talking with the casting facilities at WPI, We discovered that it would take approximately 7 days for a single cast to be made with the facilities on campus. This involved a preparation process of forming a sand mold using a wax investment, fully melting the investment out of the cast, and preparing the aluminum. Additionally, a program must be run to evaluate the movement of the molten aluminum through the cast to make sure enough material would make it through to the part. Overall, this process is done at an extremely small scale and can be easily improved to be more efficient and take much less time per part at an industrial scale. In a die cast facility like previously described to estimate our costs, the molds are machined and used over and over unlike the sand casting process done on campus.

### 4.3.2 Additive Piston Cost Model

By using the online quoting services of Stratasys, Protolabs, Craftcloud, and Fathom, we uploaded the 3D model of an automotive piston shown in the methodology section with the manufacturing specifications outlined in the methodology section. We asked for four quotes from each company regarding the different quantities of parts that we were looking to compare. Some companies gave more information than others regarding the different quantities and lead times to produce the parts.

**Table 13:** *Stratasys Quote*

| **Quantity** | **# of Pistons** | **4** | **20** | **80** | **400** |
|---|---|---|---|---|---|
| **Lead time** | **days** | N/A | N/A | N/A | N/A |
| **Associated cost per part** | **$/part** | $1,524 | $1,501 | $1,496 | $1,495 |

*Note*. This table displays the data received from the quote provided by the online quoting service on Stratasys' website based on the 3D model provided. (*Appendix A*)

**Table 14:** *Protolabs Quote*

| **Quantity** | **# of Pistons** | **4** | **20** | **80** | **400** |
|---|---|---|---|---|---|
| **Lead time** | **days** | 12 | 30 | N/A | N/A |
| **Associated cost per part** | **$/part** | $1,167.70 | $596.63 | N/A | N/A |

*Note*. This table displays the data received from the quote provided by the online quoting service on Protolabs' website based on the 3D model provided. (*Appendix B)*

**Table 15:** *Craftcloud Quote*

| **Quantity** | **# of Pistons** | **4** | **20** | **80** | **400** |
|---|---|---|---|---|---|
| **Lead time** | **days** | 5-9 | 6-10 | 9-13 | 11-15 |
| **Associated cost per part** | **$/part** | $186.68 | $177.65 | $172.27 | $166.52 |

*Note*. This table displays the data received from the estimates provided by the online quoting service on Craftcloud's website based on the 3D model provided. (*Craftcloud*)

**Table 16:** *Fathom Quote*

| **Quantity** | **# of Pistons** | **4** | **20** | **80** | **400** |
|---|---|---|---|---|---|
| **Lead Time** | **days** | 6 | 12 | 48 | 240 |
| **Associated cost per part** | **$/part** | $1,440.48 | $1,037.22 | $1,037.22 | $1,037.22 |

*Note*. This table displays the data received from the quote provided by the online quoting service on Fathom's website based on the 3D model provided. (*Appendix C*)

According to research done by a group from the University of Alabama and Shandong University, additive manufacturing using AlSi10Mg powder consumes about 566.2 MJ/kg. Since the model used for this project weighs 411g, this means the part consumes about 233MJ or 64.4kWh of energy per part. If the manufacturing were done in Massachusetts, where the average cost of electricity comes to 17.6¢. Table 12 below shows the estimated cost of electricity needed to produce different quantities of automotive pistons using additive manufacturing.

**Table 17:** *Estimated Cost of Electricity Through Additive Manufacturing*

| **# of Pistons** | 1 | 4 | 20 | 80 | 400 |
|---|---|---|---|---|---|
| **Energy Used in kWh** | 64.4 | 258 | 1,288 | 5,152 | 25,760 |
| **Estimated Electricity Cost** | $11.33 | $45.34 | $226.69 | $906.75 | $4,533.76 |

*Note*. This table shows the estimated cost of electricity needed to produce the different quantities of automotive pistons using additive manufacturing.

Another data point for additive manufacturing of the automotive pistons was gathered through a discussion with Lin Cheng and calculations based on data that was given from that discussion. Unfortunately the capabilities of this printer associated with WPI do not allow it to reasonably fill the requirements for this project, so it was not included in any of the tables or conversations before here. The printer available is only capable of printing one piston at a time. With a print time of 37 hours and an associated cost per part of $12,000 coming from a $250,000 machine, this shows the highest possible cost for 3D printing to an individual looking to print a single piston. This data point is an outlier and should be disregarded due to the fact that there are multiple companies that we contacted who could produce a single part for much cheaper.

### 4.3.3 Piston Cost Model Comparison

The information from the previous two sections has been combined into Table 17 below. Relative information from additive manufacturing has been included from the electricity estimation and Fathom as it has the most whole and reasonable data.

**Table 18**: *Cost Comparison Between Casting and Fathom Quote*

| Traditionally Manufactured Pistons | | | | |
|---|---|---|---|---|
| # of Pistons | 4 | 20 | 80 | 400 |
| Time to Manufacture | 45 | 45 | 50 | 60 |
| Energy used (kWh) | 0.82 | 4.1 | 16.4 | 82.2 |
| Total Cost per Piston | $50,004.27 | $50,020.8 | $50,085 | $50,416.78 |
| Additively Manufactured Pistons: Fathom | | | | |
| # of Pistons | 4 | 20 | 80 | 400 |
| Time to Manufacture | 6 days | 12 days | 48 days | 240 days |
| Energy Used (kWh) | 258 | 1,288 | 5,152 | 25,760 |
| Total Cost | $5,761.92 | $20,744.4 | $82,977.6 | $414,888 |

*Note*. This table displays the differences in time, energy use, and total cost for each of the different quantities of piston.

## 4.4 Resulting Piston Life Cycle Analysis

Due to a lack of response from casting companies and very little information provided by additive manufacturing companies, we have very little information to analyze for the life cycle analysis. The positives for both processes is that there is only material being worked with and none of the processes involved in creating the piston have any sort of chemical reaction that could produce waste. For both additive and traditional manufacturing, the aluminum waste that is not used to make the final part is able to be thrown directly back into the supply used to create the pistons or other parts using the same material.

For additive manufacturing, the energy required to produce the part is much higher than the energy required to heat the aluminum for casting. This is due to the fact that the piston is being assembled layer by layer instead of all at once. This means that each part takes dozens of hours to make with a high intensity laser running for that entire time. So depending on where the company sources their electricity, This aspect of the production would have a great effect on the pollution caused by the production. According to our calculations, the energy consumption of the additive manufacturing is approximately 314 times as large as the traditional manufacturing. The most abundant source of electricity in Massachusetts is natural gas (*U.S. Department of Energy.*). Natural gas pollutes 0.91lbs of $CO_2$ per kWh produced (*U.S. Energy Information Administration*. (2021)). So this means that each additive manufactured part produces 58.6lbs of $CO_2$ while each die cast part produces about 0.2lbs of $CO_2$.

The only other substance that is used in either of the processes is argon gas used during the laser sintering in additive manufacturing. Fortunately, this gas does not have any negative environmental impacts. It is naturally occuring in the atmosphere and the third most abundant gas behind nitrogen and oxygen at about 1% of earth's atmosphere *(Top uses of Argon Gas (2021)).* The argon gas is used as a shielding gas to protect the molten aluminum alloy from reacting with the oxygen in the air. In the SLM 280 metal 3D printer, this gas is used at a rate of 2.5 liters/min during the printing process and at a rate of 70 liters/min during the purging process which takes place over a much shorter time (*SLM280* (2022)). Due to Argon's natural abundance and inert nature with very little effect on the climate of the earth, this aspect of 3D printing can essentially be ignored.

## 5.0 Impacts

With every project, the impacts should be considered and written into the report. For our impacts, they can be broken down into engineering ethics, societal and global impact, environmental impact, codes and standards, and economic factors. The following sections will discuss these topics in depth and mention how they correlate to our project.

### 5.1 Engineering Ethics

The Mechanical Engineering Code of Ethics states that engineers should uphold and advance the integrity, honor, and dignity of the engineering profession. This is done by 1. using their knowledge and skill for the enhancement of human welfare, 2. being honest and impartial, and serving with fidelity their clients (including their employers) and the public; and 3. striving to increase the competence and prestige of the engineering profession (Khan, A., 2022). In our report, we ensured transparency in our data by clearly stating how we received it, how we came up with it, and if there were any uncertainties when reporting our findings.

### 5.2 Societal and Global Impact

In regards to our first case study, printed circuit boards, we hope to positively impact consumers who purchase PCBs as well as the health and welfare of everyone. We intended to inform others about both manufacturing processes, traditional and additive, and provide a PCB case study that detailed cost analyses and life cycle analyses for both processes. We broke the information into two parts to shine a light on the benefits and fallings short for both processes, as well as to discuss them in depth. At the time of conducting our MQP, papers that discuss additive versus traditional manufacturing for PCB’s exist, but none of the reports include a case study with numbers to back up their claims. Unintended consequences for our project may include promoting or demoting certain companies by their inclusion in our project. In our procedure we named the companies we contacted for research purposes, and stated that a lot of them did not get back to us. We meant no harm to those companies, however the simple statement of fact is that it may paint those companies in an uncomfortable light and paint those that responded in a better one.

### 5.3 Environmental Impact

Our project revolves around assessing the environmental impact of manufacturing processes. By creating life cycle analyses, we hope it will positively impact the environment by helping companies make informed decisions when it comes to the manufacturing or purchase of printed circuit boards and pistons. We aim to inform people in the short term in the hopes that our report may lead to long term sustainability in manufacturing.

### 5.4 Codes and Standards

For our first case study, IPC standards govern the work related to PCB manufacturing. It was named after the association that produces PCB-related standards, the Institute for Printed Circuits. The association is now called the Association Connecting Electronics Industries but they decided to continue calling them IPC standards. The best description of these standards comes from the website All About Circuits, “IPC standards are the electronics-industry-adopted standards for design, PCB manufacturing, and electronic assembly. There's an IPC standard associated with just about every step of PCB design, production, and assembly,” (*The History* *and Basics of IPC Standards*, 2017). Four leading benefits of the standards are; improved product quality and reliability, improved communication, reduced costs, and improved reputation and new opportunities (*IPC Standards for Printed Circuit Boards*, 2019).

ISO standards 14040 and 14044 apply to our project, as they define a complete life cycle analysis when following a product from cradle to grave. “ISO 14040 describes the ‘principles and framework for LCA’, while the ISO 14044 ‘specifies requirements and provides guidelines’ for LCA,” (*Life Cycle-Based Sustainability Standards and Guidelines*, 2021). ISO standard 14067 may also apply. It is consistent with the other two ISO standards and also includes requirements on issues related to carbon footprints and a product's impact on climate change. Although our project did study PCBs environmental impacts, we were unable to create a complete life cycle analysis study as defined by the ISO standards. The life cycle we use for the PCB case study is for a gate to gate analysis and not a cradle to grave, as we did not have sufficient data or external review.

### 5.5 Economic Factors

Our project is also centered around economic factors. The cost of manufacturing, set-up, shipping, and electricity were all considered in our project's cost analyses. We realize that there are many factors that can influence cost when making a part, such as size or how many holes need to be drilled when referring to PCB’s. We include all of these factors in our cost models in order to provide a better cost breakdown to both consumers and companies. Our aim is to help anyone make informed choices in both an environmental and economic sense when manufacturing either additively or traditionally for printed circuit boards and engine pistons.

## 6.0 Conclusion

It is recommended that another MQP picks up where we left off and continues our research with other types of PCBs in addition to aluminum pistons. Two PCB designs we believe would be the most beneficial to use are one that is multilayer and has a complex design, and another that is multilayer with a complex design and complex geometry. For a timeframe, we believe it should be picked up in a few years, where at that point we hope it will be easier to conduct the research and analyses. There will also hopefully be more than one AME company that manufactures printed circuit boards at that time, where data can then be compared and averaged between companies for less biased analyses. Similarly, metal additive manufacturing will hopefully advance to a more widespread

## 6.1 Concluding Remarks: PCB Case Study

Based on the information we did have, it is abundantly clear that traditional manufacturing is the most cost effective when it comes to fabricating PCBs, while additive manufacturing has a more eco-friendly life cycle. With that being said, we can only conclude this based on a single layer, simple geometry and simple design board with a gate to gate life cycle analysis. If this project were to be expanded on, we would recommend that the life cycle analyses are completed from cradle to grave or at least from cradle to gate. It is also recommended that the procedure is done again with a multilayer, complex design board, and once more with a multilayer, complex geometry, complex design board. In the first instance, it is hypothesized that the costs wouldn’t have as big of a gap as it did with the simple board, and additive may win out for both cost effectiveness and environmental friendliness. In the second instance, there may be no contest in the regard that traditional manufacturing simply cannot create highly complex geometries and cannot compete. The additive manufacturing of electronics has the ability to stack integrated circuits and their traces on an irregular surface or a structural substrate through 3D integration. This allows for a greater flexibility of mechanical drawings and new possibilities for PCB designs.

When comparing their environmental impact and life cycle analyses, additive takes a substantial lead, saving over 80% in almost every area. By using additive manufacturing to make printed circuit boards, the potential of harming the environment with wet chemicals during manufacturing is greatly reduced, and their use of conductive ink in the place of copper also creates virtually zero waste generation. Aside from a higher initial cost, the additive manufacturing of electronics is generally more eco-friendly, has a faster production, and is more precise than traditional manufacturing.

The resulting analyses for our PCB case study are slightly dissatisfying due to a lack of data and available resources. The traditional cost analysis and life cycle analysis are a little dated, as companies were not able to get back to us regarding the specific manufacturing questions we had. We subsequently had to use information from a research paper dated from 2018, containing values that have most likely changed over the course of four years. The numbers also did not reflect the PCB we used, which was discouraging. The life cycle analysis we did receive seemed to be for a gate to gate analysis and not a cradle to grave one, and also used a different PCB model than the one we chose. Most companies were also unable to give us machine costs, costs associated with each manufacturing step, the amount of input and output materials, the energy consumed for each process, and the number of scrapped PCBs. It is possible that companies did not want to make this information public, so as to not create more competition for themselves.

To get around these obstacles, we had to predominantly use public manufacturing capability information on the different company websites, along with a few online PCB websites to give us quotes for the PCB design we selected. The technology for the additive manufacturing of printed circuit boards is not as prominent as it needs to be to create accurate cost models and life cycle analyses. We were only able to find two companies that additively manufactured PCBs, Nano Dimension and Optomec. Optomec was not able to give us manufacturing information or provide us with quotes, as they only manufacture the machines, so our data is entirely from Nano Dimension. After contacting Nano Dimension and working with them, they suggested checking out TTM Technologies, and described that they can manufacture PCBs using both manufacturing methods. Since we were unable to compare a few different AME companies and find average values or costs, this can cause a slight bias in our data. At the time of our research, Nano Dimension is a new and upcoming company, and they are still expanding, recruiting more staff, and solidifying their rates. Although promising, AME technology is still new and has a higher cost, so a major switch to additive manufacturing in the industry will happen, but maybe not for at least a few years.

### 6.2 Concluding Remarks: Piston Case Study

From our research, we are able to conclude that die casting is more eco friendly than additive manufacturing, assuming the plant is using electric furnaces and machinery to bring the metal to its casting temperature and actually go through the casting process. We also found that it is more cost effective to go with die casting when producing a volume of parts in a quantity of at least 80, and the point where die casting becomes more cost effective may be even lower as the flipping point occurs sometime between 20 and 80 parts produced. The lead times of parts are equivalent at around the 80 parts produced quantity at around 45-50 days. Anything more is quicker to produce using die casting as it has a much higher output rate once the die is machined. Fathom gave us a flat part/time rate, so the time increases in a linear fashion whereas the die casting time increases at more of a logarithmic rate. This is in line with current assumptions about additive manufacturing and how it is almost exclusively used as a means of prototyping a part in a quicker and more cost effective form as minor changes made to the model between iterations can lead to massive costs in die casting when an entirely new die must be machined.

The analyses made about pistons are not quite what we had hoped to achieve in the course of our project as a lot of the companies that we reached out to for information were unable to provide us with the in depth information that we were requesting either because they did not have it available to share or because they were unwilling to share it with us for confidentiality or non-competition reasons. Because of this, we ended up using basic quotes and a study done on die casting facilities almost 20 years ago. This information was definitely helpful, and newer versions of the die casting information would most likely even further support our conclusion that die casting is more beneficial for manufacturing, and it would most likely drop the flipping point closer to 20 parts than we concluded in this project.

We believe this research should be picked up again for the manufacture of pistons in 10-20 years when the technology surrounding metal printing has had time to advance further. After that time, we expect that the metal 3d printing industry will have advanced far enough that they may be at the same level of access and simplicity that current day FDM printers with PLA filament are. This will allow students to conduct more physical research as WPI may invest in recreational metal printers as they have at the makerspace in The Innovation Studio. We also suggest that WPI attempt to create a partnership with traditional and additive manufacturing companies for this project to allow for an easy point of access for information. Additionally, we recommend that the future project has a focus on how the complexity that is capable with additive manufacturing can allow for lightweight parts of the same strength as well as improved cooling capabilities. These benefits that are only capable with additive manufacturing are the main desire to work with additive manufacturing, and it would be a great way to compare the two processes from cradle to grave or at least from gate to grave. This expanded lifespan analysis of the piston would show us how a lightweight piston could save energy through the 200,000 mile lifespan that modern engines are easily capable of achieving.

Additive manufacturing is very promising for the future of manufacturing, but it is unfortunately not yet at the point where mass manufacturing of parts is feasible or cost effective. We hope this will change in the near future and bring with it a wave of more efficient parts in all aspects of manufacturing - not just automotive.

## 7.0 Acknowledgements

We would like to thank WPI staff for their help in providing information for the manufacturing of pistons on campus. This includes Erica Stults, Lin Cheng, Yutao Wang, and Mike Collins. We would also like to thank our advisor, Adam Powell, for guiding us through this project.

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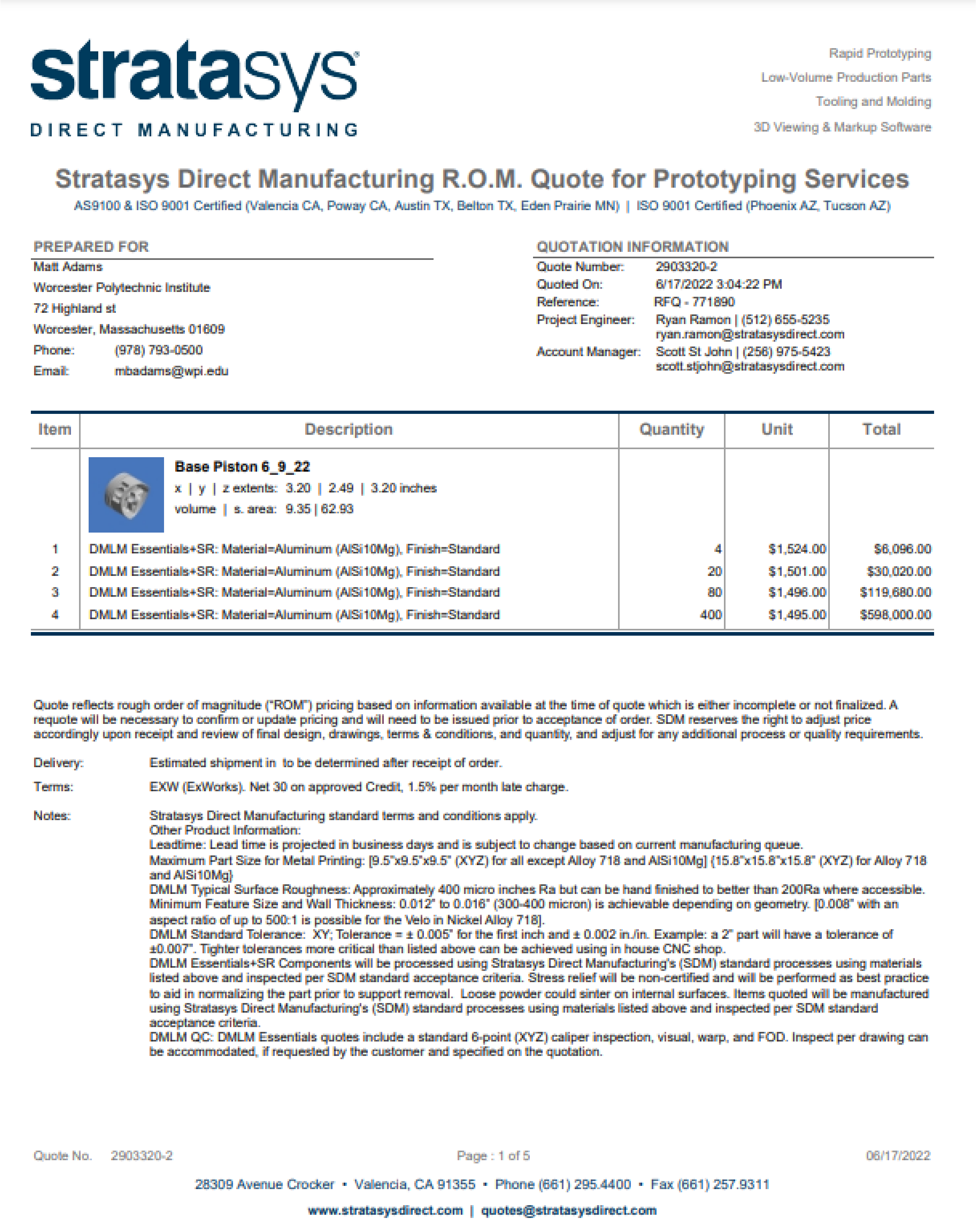
# Appendix A: Stratasys Quote



stratasys
DIRECT MANUFACTURING

Rapid Prototyping
Low-Volume Production Parts
Tooling and Molding
3D Viewing & Markup Software

## Stratasys Direct Manufacturing R.O.M. Quote for Prototyping Services

AS9100 & ISO 9001 Certified (Valencia CA, Poway CA, Austin TX, Belton TX, Eden Prairie MN) | ISO 9001 Certified (Phoenix AZ, Tucson AZ)

**PREPARED FOR**

Matt Adams
Worcester Polytechnic Institute
72 Highland st
Worcester, Massachusetts 01609
Phone: (978) 793-0500
Email: mbadams@wpi.edu

**QUOTATION INFORMATION**

Quote Number: 2903320-2
Quoted On: 6/17/2022 3:04:22 PM
Reference: RFQ - 771890
Project Engineer: Ryan Ramon | (512) 655-5235 ryan.ramon@stratasysdirect.com
Account Manager: Scott St John | (256) 975-5423 scott.stjohn@stratasysdirect.com

| Item | Description | Quantity | Unit | Total |
|---|---|---|---|---|
| | **Base Piston 6_9_22**<br>x \| y \| z extents: 3.20 \| 2.49 \| 3.20 inches<br>volume \| s. area: 9.35 \| 62.93 | | | |
| 1 | DMLM Essentials+SR: Material=Aluminum (AlSi10Mg), Finish=Standard | 4 | $1,524.00 | $6,096.00 |
| 2 | DMLM Essentials+SR: Material=Aluminum (AlSi10Mg), Finish=Standard | 20 | $1,501.00 | $30,020.00 |
| 3 | DMLM Essentials+SR: Material=Aluminum (AlSi10Mg), Finish=Standard | 80 | $1,496.00 | $119,680.00 |
| 4 | DMLM Essentials+SR: Material=Aluminum (AlSi10Mg), Finish=Standard | 400 | $1,495.00 | $598,000.00 |

Quote reflects rough order of magnitude ("ROM") pricing based on information available at the time of quote which is either incomplete or not finalized. A requote will be necessary to confirm or update pricing and will need to be issued prior to acceptance of order. SDM reserves the right to adjust price accordingly upon receipt and review of final design, drawings, terms & conditions, and quantity, and adjust for any additional process or quality requirements.

Delivery: Estimated shipment in to be determined after receipt of order.

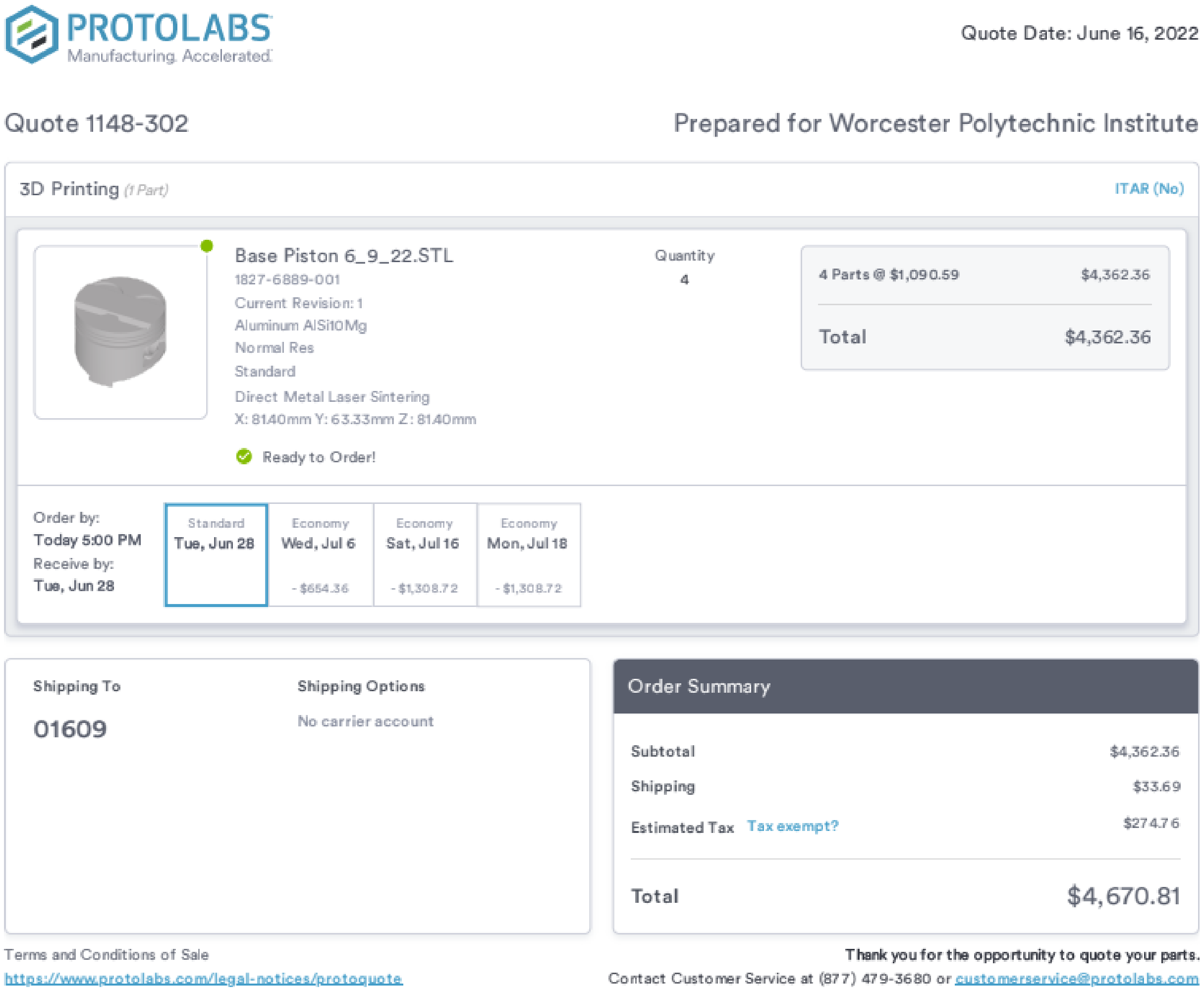
Terms: EXW (ExWorks). Net 30 on approved Credit, 1.5% per month late charge.

Notes: Stratasys Direct Manufacturing standard terms and conditions apply.
Other Product Information:
Leadtime: Lead time is projected in business days and is subject to change based on current manufacturing queue.
Maximum Part Size for Metal Printing: [9.5"x9.5"x9.5" (XYZ) for all except Alloy 718 and AlSi10Mg] {15.8"x15.8"x15.8" (XYZ) for Alloy 718 and AlSi10Mg}
DMLM Typical Surface Roughness: Approximately 400 micro inches Ra but can be hand finished to better than 200Ra where accessible.
Minimum Feature Size and Wall Thickness: 0.012" to 0.016" (300-400 micron) is achievable depending on geometry. [0.008" with an aspect ratio of up to 500:1 is possible for the Velo in Nickel Alloy 718].
DMLM Standard Tolerance: XY; Tolerance = ± 0.005" for the first inch and ± 0.002 in./in. Example: a 2" part will have a tolerance of ±0.007". Tighter tolerances more critical than listed above can be achieved using in house CNC shop.
DMLM Essentials+SR Components will be processed using Stratasys Direct Manufacturing's (SDM) standard processes using materials listed above and inspected per SDM standard acceptance criteria. Stress relief will be non-certified and will be performed as best practice to aid in normalizing the part prior to support removal. Loose powder could sinter on internal surfaces. Items quoted will be manufactured using Stratasys Direct Manufacturing's (SDM) standard processes using materials listed above and inspected per SDM standard acceptance criteria.
DMLM QC: DMLM Essentials quotes include a standard 6-point (XYZ) caliper inspection, visual, warp, and FOD. Inspect per drawing can be accommodated, if requested by the customer and specified on the quotation.

Quote No. 2903320-2 Page : 1 of 5 06/17/2022

28309 Avenue Crocker • Valencia, CA 91355 • Phone (661) 295.4400 • Fax (661) 257.9311
www.stratasysdirect.com | quotes@stratasysdirect.com

# Appendix B: Protolabs Quote



PROTOLABS
Manufacturing. Accelerated.

Quote Date: June 16, 2022

Quote 1148-302

Prepared for Worcester Polytechnic Institute

3D Printing *(1 Part)*

ITAR (No)

Base Piston 6_9_22.STL
1827-6889-001
Current Revision: 1
Aluminum AlSi10Mg
Normal Res
Standard
Direct Metal Laser Sintering
X: 81.40mm Y: 63.33mm Z: 81.40mm

✓ Ready to Order!

Quantity
4

| | |
|---|---|
| 4 Parts @ $1,090.59 | $4,362.36 |
| Total | $4,362.36 |

Order by:
Today 5:00 PM
Receive by:
Tue, Jun 28

| Standard | Economy | Economy | Economy |
|---|---|---|---|
| Tue, Jun 28 | Wed, Jul 6 | Sat, Jul 16 | Mon, Jul 18 |
| | - $654.36 | - $1,308.72 | - $1,308.72 |

**Shipping To**

01609

**Shipping Options**

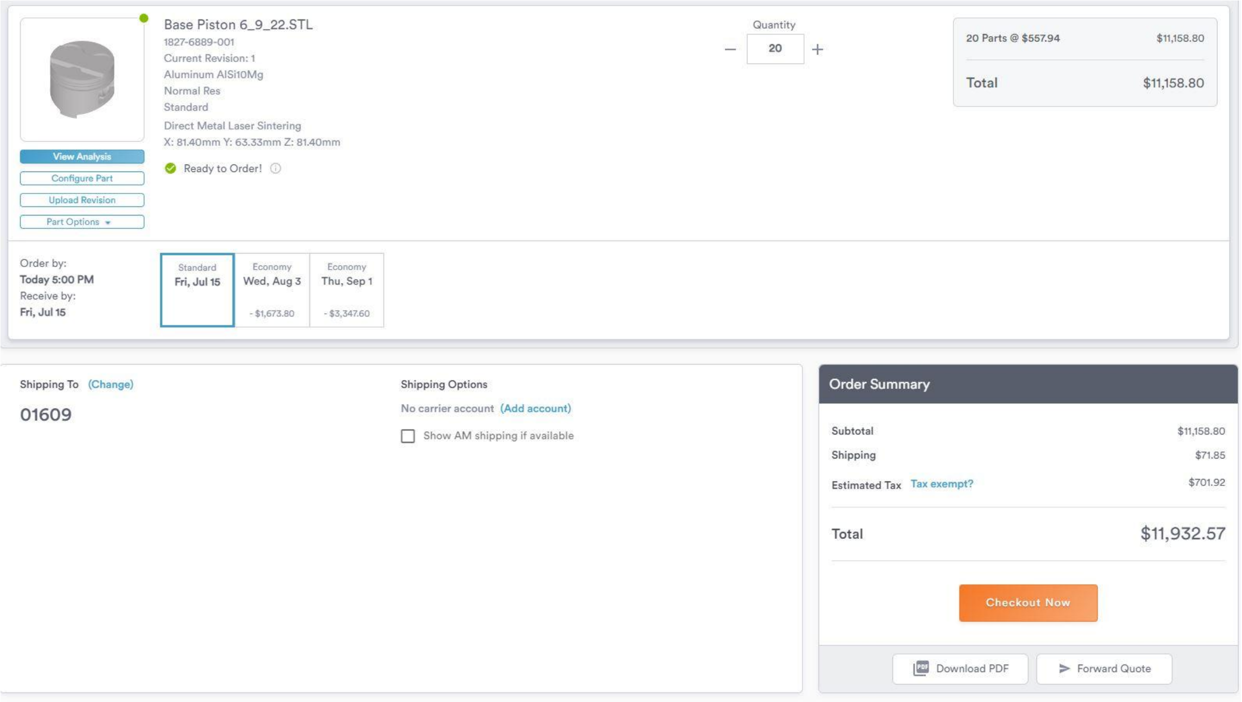
No carrier account

Order Summary

| | |
|---|---|
| Subtotal | $4,362.36 |
| Shipping | $33.69 |
| Estimated Tax Tax exempt? | $274.76 |
| Total | $4,670.81 |

Terms and Conditions of Sale
https://www.protolabs.com/legal-notices/protoquote

**Thank you for the opportunity to quote your parts.**
Contact Customer Service at (877) 479-3680 or customerservice@protolabs.com



Base Piston 6_9_22.STL
1827-6889-001
Current Revision: 1
Aluminum AlSi10Mg
Normal Res
Standard
Direct Metal Laser Sintering
X: 81.40mm Y: 63.33mm Z: 81.40mm

✓ Ready to Order! ⓘ

Quantity
– 20 +

| | |
|---|---|
| 20 Parts @ $557.94 | $11,158.80 |
| Total | $11,158.80 |

Order by:
Today 5:00 PM
Receive by:
Fri, Jul 15

| Standard | Economy | Economy |
|---|---|---|
| Fri, Jul 15 | Wed, Aug 3 | Thu, Sep 1 |
| | - $1,673.80 | - $3,347.60 |

Shipping To (Change)

01609

Shipping Options

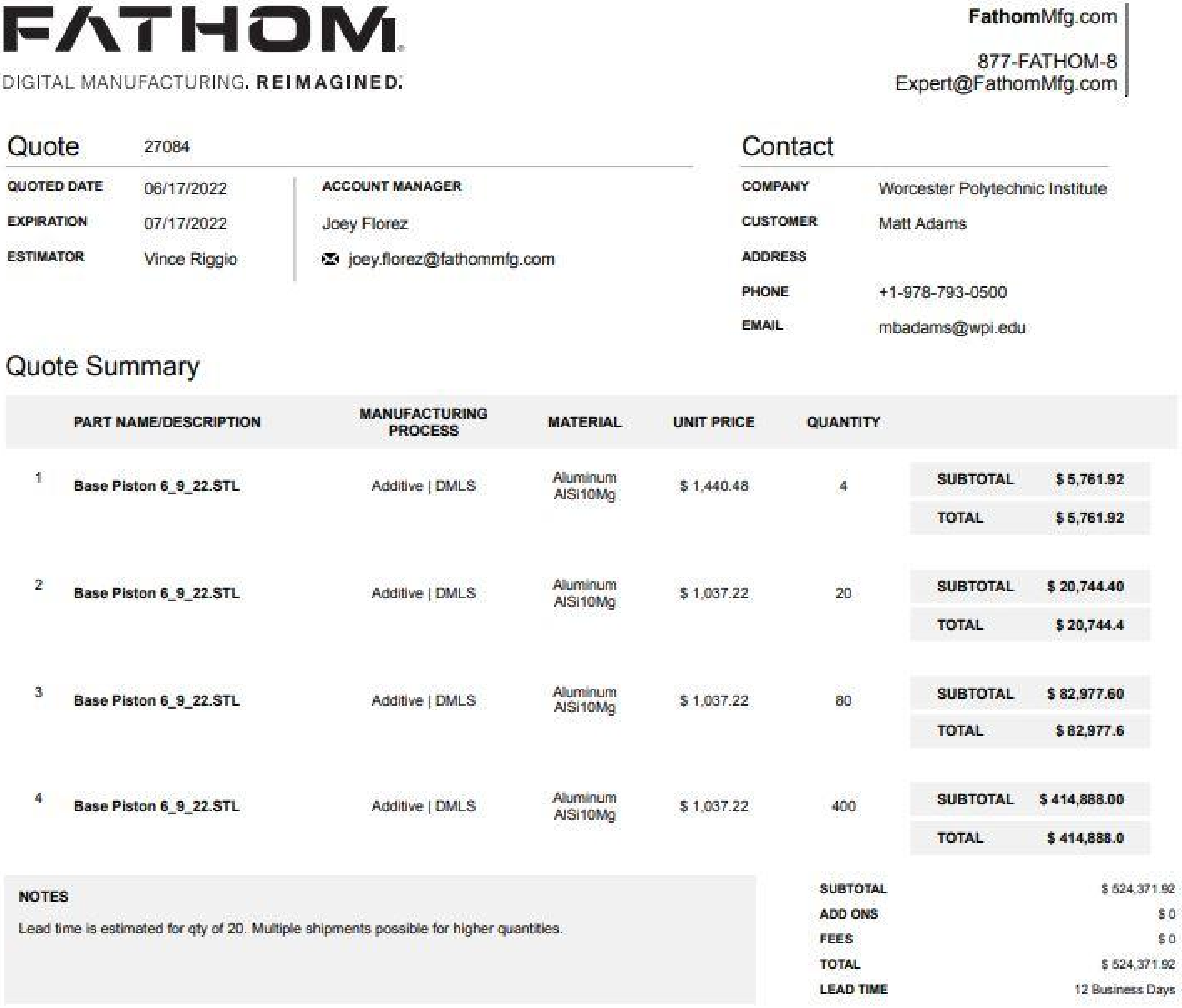
No carrier account (Add account)

☐ Show AM shipping if available

Order Summary

| | |
|---|---|
| Subtotal | $11,158.80 |
| Shipping | $71.85 |
| Estimated Tax Tax exempt? | $701.92 |
| Total | $11,932.57 |

## Appendix C: Fathom Quote



**FATHOM**
DIGITAL MANUFACTURING. **REIMAGINED.**

**Fathom**Mfg.com
877-FATHOM-8
Expert@FathomMfg.com

## Quote 27084

| | |
|---|---|
| **QUOTED DATE** | 06/17/2022 |
| **EXPIRATION** | 07/17/2022 |
| **ESTIMATOR** | Vince Riggio |

**ACCOUNT MANAGER**
Joey Florez
✉ joey.florez@fathommfg.com

## Contact

| | |
|---|---|
| **COMPANY** | Worcester Polytechnic Institute |
| **CUSTOMER** | Matt Adams |
| **ADDRESS** | |
| **PHONE** | +1-978-793-0500 |
| **EMAIL** | mbadams@wpi.edu |

## Quote Summary

| | PART NAME/DESCRIPTION | MANUFACTURING PROCESS | MATERIAL | UNIT PRICE | QUANTITY | | |
|---|---|---|---|---|---|---|---|
| 1 | **Base Piston 6_9_22.STL** | Additive \| DMLS | Aluminum AlSi10Mg | $ 1,440.48 | 4 | **SUBTOTAL**<br>**TOTAL** | **$ 5,761.92**<br>**$ 5,761.92** |
| 2 | **Base Piston 6_9_22.STL** | Additive \| DMLS | Aluminum AlSi10Mg | $ 1,037.22 | 20 | **SUBTOTAL**<br>**TOTAL** | **$ 20,744.40**<br>**$ 20,744.4** |
| 3 | **Base Piston 6_9_22.STL** | Additive \| DMLS | Aluminum AlSi10Mg | $ 1,037.22 | 80 | **SUBTOTAL**<br>**TOTAL** | **$ 82,977.60**<br>**$ 82,977.6** |
| 4 | **Base Piston 6_9_22.STL** | Additive \| DMLS | Aluminum AlSi10Mg | $ 1,037.22 | 400 | **SUBTOTAL**<br>**TOTAL** | **$ 414,888.00**<br>**$ 414,888.0** |

**NOTES**

Lead time is estimated for qty of 20. Multiple shipments possible for higher quantities.

| | |
|---|---|
| **SUBTOTAL** | $ 524,371.92 |
| **ADD ONS** | $ 0 |
| **FEES** | $ 0 |
| **TOTAL** | $ 524,371.92 |
| **LEAD TIME** | 12 Business Days |