UTILIZING ADDITIVE MANUFACTURING TO INCREASE PROCESS FLEXIBILITY

by

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LIST OF ABBREVIATIONS

3D	Three-dimensional
ABS	Acrylonitrile Butadiene Styrene (Plastic Material)
AM	Additive Manufacturing
AMF	Additive Manufacturing Facility
CNC	Computer Numerical Control
CAD	Computer-Aided Design
DMLS	Direct Metal Laser Sintering
EOS	Electro Optical Systems
FDM	Fused Deposition Modeling
ISS	International Space Station
MPa	Megapascal
NAE	National Academy of Engineering
NASA	National Aeronautics and Space Administration
PA	Polyamide (Plastic Material)
PC	Polycarbonate (Plastic Material)
PE	Polyethylene (Plastic Material)
PP	Polypropylene (Plastic Material)
SLA	Stereolithography Apparatus
SLS	Selective Laser Sintering
QCO	Quick Changeover
ROI	Return on Investment
UV	Ultraviolet

GLOSSARY

Additive manufacturing	The process of joining material layer by layer, using data from a 3D model (Bikas et al., 2015).
Density	The mass of a component per unit volume (Olsen, 2020).
Elongation at Break	The amount deformation, or change in part length at breakage (Olsen, 2020).
Megapascal (MPA)	A unit of pressure. The megapascal is one million pascals, or one million newtons per square meter (DeWood, 2014).
Traditional manufacturing	The process of cutting away from a block of material to achieve the desired shape (Bikas et al., 2015).
Ultimate Tensile Strength	The amount of load at which breakage occurs (Olsen, 2020).
Yield Strength	The amount of load at which permanent deformation occurs (Olsen, 2020).

ABSTRACT

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The future of manufacturing will be a transformation from traditional machines to smart systems (Jeschke et al., 2017). Smart manufacturing brings new technologies that include automation, additive manufacturing, and smart machines that communicate with one another (Gilchrist, 2016). Additive manufacturing is the process of joining material layer by layer, using data from a three-dimensional model, to create a part (Bikas et al., 2015). The different additive manufacturing methods available including fused deposition modeling (FDM), stereolithography apparatus (SLA), selective laser sintering (SLS), and metal binder jetting (Bikas et al., 2015). Materials used in additive manufacturing include polymers, metal alloys, ceramics, and biomedical (Ngo et al., 2018). The research included four aerospace case study examples that used additive manufacturing to improve their process and part design. All four examples used the same 3D printer, the Electro Optical Systems EOS M 400 direct laser sintering machine for industrial production (Electro Optical Systems, 2020b). The materials used in the research varied among aluminum alloy, titanium alloy, and nickel-based alloy. The results show a significant reduction in manufacturing time, up to a 97%, and reduction in part cost, up to a 99%. The return on investment of implementing additive manufacturing can be seen as low as five weeks. The results also provide areas for future research including functional testing, additional additive manufacturing technologies and additional material types.

CHAPTER 1. INTRODUCTION

1.1 The Problem

The future of manufacturing will be a transformation from traditional machines to smart systems (Jeschke et al., 2017). Fully integrated, automated facilities will communicate with one another and boost flexibility, speed, productivity, and quality (Rüßmann et al., 2015). Smart manufacturing will depend on an increase in process flexibility to decrease lot sizes, and quick changeover (QCO) (Jeschke et al., 2017). Product development lead time and flexibility on traditional manufacturing processes are falling behind the pace of technology innovation (Macleod, 2020). Smart manufacturing brings new technologies that include automation, additive manufacturing, and smart machines that communicate with one another (Gilchrist, 2016).

Additive manufacturing, also known as three-dimensional (3D) printing, is the process of printing parts layer-by-layer from detailed computer aided design (CAD) models (Macleod, 2020). Three-dimensional printing allows for rapid production of customized objects by simply uploading a new 3D CAD file in the software (Gilchrist, 2016). Changes to a product design can require weeks of work refitting traditional manufacturing production lines and reconfiguring machines (Gilchrist, 2016). Three-dimensional printing enables lot sizes of one part to be profitable and cost effective (Gilchrist, 2016). Additive manufacturing changes the thinking at the product design level as well as manufacturing. The way that a 3D printer builds a part one layer at a time can eliminate some of the limitations of traditional manufacturing machines (Macleod, 2020). Product assemblies containing several different parts can be printed as a single component, eliminating the assembly time (Ngo et al., 2018). Additive manufacturing provides an efficient and economic method to produce complex geometries with advanced properties and minimal material wastage (Jeschke et al., 2017).

1.2 The Impact of The Problem

The impact of additive manufacturing can be seen on several elements of the manufacturing process. Additive manufacturing materials and equipment has evolved over the years to offer increased design freedom, reduced lead times, and less material waste (Bikas et al., 2015). Three-dimensional printed parts can be used in a variety of applications with material that include plastics, metals, and even biomedical materials (Ngo et al., 2018). Implementing additive manufacturing to a process can reduce the number of parts in an assembly, reduce lead times, and reduce material waste (Ngo et al., 2018).

Access to 3D printing enables manufacturers to develop prototypes and proof of concept designs during the product design process (Gilchrist, 2016). The prototypes and proof of concept designs greatly reduce design time and engineering effort (Gilchrist, 2016). Manufacturing processes and limitations influence the way that products are designed. New technologies, such as additive manufacturing, can overcome the limitations of traditional machines and reduce the number of required parts (Ngo et al., 2018). The process of building one layer at a time can produce geometry that milling machines and mold tools are unable to reach (Ngo et al., 2018). The layer process can also increase the complexity of the parts long as the geometry can be created in the CAD models (Ngo et al., 2018). For example, General Electric was able to reduce the part count from 20 to one on a fuel nozzle using additive technology (Mahoney, et al., 2017).

The production process can also benefit from using smart technologies like additive manufacturing. Additive manufacturing enables production of small batches of customized products (Gilchrist, 2016). The customized products offer more value to customers, while reducing cost and manufacturing time (Gilchrist, 2016). The 3D printing process can switch over from different part types with minimal set up time (Jeschke et al., 2017). The flexibility of 3D printers can allow for changeover from customer specific demands (Jeschke et al., 2017). Some 3D printers can be loaded with multiple material types to further increase the efficiency (Ngo et al., 2018). Depending on the part size and the printer's build area, multiple parts of various specifications can be printed at the same time (Ngo et al., 2018). To go a step further, automation can be used in the printing process. The 3D printer queue can be loaded with multiple print jobs and robots can be used to remove the build tray (Gilchrist, 2016). The process flexibility and use of automation makes additive manufacturing a great candidate for smart manufacturing systems.

Another benefit to implanting smart manufacturing is the reduction in waste throughout the process. Traditional metal machining is a subtractive process (Abdulhameed et al., 2019). Starting with a block or bar of raw material and cutting away scrap until the desired shape is achieved (Abdulhameed et al., 2019). Three-dimensional printing builds up one layer at a time producing only the required geometry. Kearney describes 3D printing as "a process that has the potential to produce little to no waste and is capable of recycling materials" (Kearney, 2017, p. 18). Eliminating material waste will save money in areas such as machining time and raw material quantities purchased.

As additive manufacturing technology is continuously developed, more applications are emerging (Ngo et al., 2018). Additive manufacturing's versatility is apparent in the application "across a diverse array of industries including electronics, energy, nanotechnology, aerospace and many others" (Jeschke et al., 2017, p. 672). Three-dimensional printers can speed up production time by creating proof of concept prototypes of architectural buildings and consumer products (Gilchrist, 2016). One of the more extreme applications of 3D printing methodology is in the health and biomedical industries (Ngo et al., 2018). Three-dimensional printers are used to create medical implants and prosthetics (Mahoney, et al., 2017). The biomedical applications rely heavily on the flexibility concepts from smart manufacturing, as each product is customized for the patient (Ngo et al., 2018). Another industry that uses of additive manufacturing is the aerospace industry (Ngo et al., 2018). Additive manufacturing techniques are ideal for aerospace components as the part designs have complex geometry and small batch sizes (Ngo et al., 2018).

1.3 How The Problem is Measured

The effects of additive manufacturing can be measured in several ways that can save a company money (Kearney, 2017). One 3D printer can completely build a part with complex geometry, eliminating multiple steps in the process (Abdulhameed et al., 2019). Manufacturing cost and time are saved through elimination of rough machining and a reduction in the programming effort (Abdulhameed et al., 2019). Companies in the aerospace industry are including additive manufacturing in the production process to reduce manufacturing time as high as 75% (Ngo et al., 2018). Additive manufacturing can reduce the product costs for high-volume and low-volume parts in addition to increasing the productivity of the aerospace sector (Abdulhameed et al., 2019).

For example, Airbus utilized additive manufacturing to build the A350 XWB bracket in an aluminum alloy material (Electro Optical Systems, 2018a). The sheet metal bracket with rivets attached was reduced from 30 parts to one single printed part and a 30% weight reduction (Electro Optical Systems, 2018a). The entire process to design and build a prototype took only two weeks (Electro Optical Systems, 2018a). The bracket was built in only 19 hours of production time, compared to 70 days for the previous design (Electro Optical Systems, 2018a).

The additive process of building the parts layer by layer reduces the amount of material waste (Ngo et al., 2018). The aerospace industry uses costly materials, such as titanium alloys, nickel-based alloys, steel alloys and ceramics that can be difficult to manufacture (Ngo et al., 2018). The traditional manufacturing process can create up to 95% of material waste (Ngo et al., 2018). Additive manufacturing can reduce material waste down to around 10–20% (Ngo et al., 2018).

The National Aeronautics and Space Administration (NASA) has also stared using additive manufacturing to support their International Space Station (ISS) (Hurley, 2020). To support space missions each year, NASA sends nearly 7,000 pounds of spare parts to the ISS (Hurley, 2020). Including a 3D printer on the ISS could reduce the amount of costly supply missions to replace parts and tools. The ability to produce parts on demand can also reduce the amount on inventory required. The ISS keeps 29,000 pounds of spare hardware and parts on hand and another 39,000 pounds on ground to send when needed (Hurley, 2020).

The first step is to identify multiple case study examples of additive manufacturing used in the aerospace industry. After identifying the examples, the data collection will include material specifications, and the manufacturing times and costs. The additive manufacturing material specifications will be compared to the specifications from traditional manufacturing. The manufacturing time and cost data will be collected and compared. Finally, the return on investment will be calculated using the manufacturing data collected along with the 3D printer initial cost of investment.

1.4 Connectivity of The Problem with The NAE Grand Challenge

The National Academy of Engineering (NAE) has identified a list of fourteen goals for future design (National Academy of Engineering, n.d.a). The goals are known as the Grand Challenges for Engineering in the 21st century. The challenges fall into the themes of sustainability, health, security, and joy of living (National Academy of Engineering, n.d.a). One of the specific challenges focuses on engineering the tools to explore the universe (National Academy of Engineering, n.d.b). Additive manufacturing increases the availability for critical parts and tools of scientific discovery (National Academy of Engineering, n.d.b). Three-dimensional printers can be brought along on space missions to eliminate the need for spare parts on supply missions. Astronauts on long voyages need to be able to make essential spare parts and tools on demand for routine and unforeseen needs (Gaskill, 2019). The National Aeronautics and Space Administration's additive manufacturing efforts for the ISS mainly focus on the plastics materials (Hurley, 2020). The National Aeronautics and Space Administration has also teamed up with, Made in Space, to develop the Additive Manufacturing Facility (AMF) (Hurley, 2020). The AMF is a multi-material 3D printer to be used on space stations (Hurley, 2020). The use of additive manufacturing on critical space exploration missions can save money and time (Gaskill, 2019).

1.5 Summary Introduction - Research Problem Statement

Product development lead time and flexibility on traditional manufacturing processes are falling behind the pace of technology innovation (Macleod, 2020). Additive manufacturing materials and equipment has evolved over the years to offer increased design freedom, reduced lead times, and less material waste (Bikas et al., 2015). The problem can be measured by the reduction in manufacturing time, as high as 75% in some industries (Ngo et al., 2018). Additive manufacturing increases the availability for critical parts and tools of scientific discovery (National Academy of Engineering, n.d.b).

CHAPTER 2. REVIEW OF LITERATURE

2.1 Additive Manufacturing Description

Additive manufacturing is the process of joining material layer by layer, using data from a 3D model, to create a part (Bikas et al., 2015). Traditional manufacturing methods start with a block of material and cutting away (subtracting) material, resulting in a significant amount of waste. A visual example of traditional (subtractive) and additive manufacturing is shown in Figure 2.1 below.

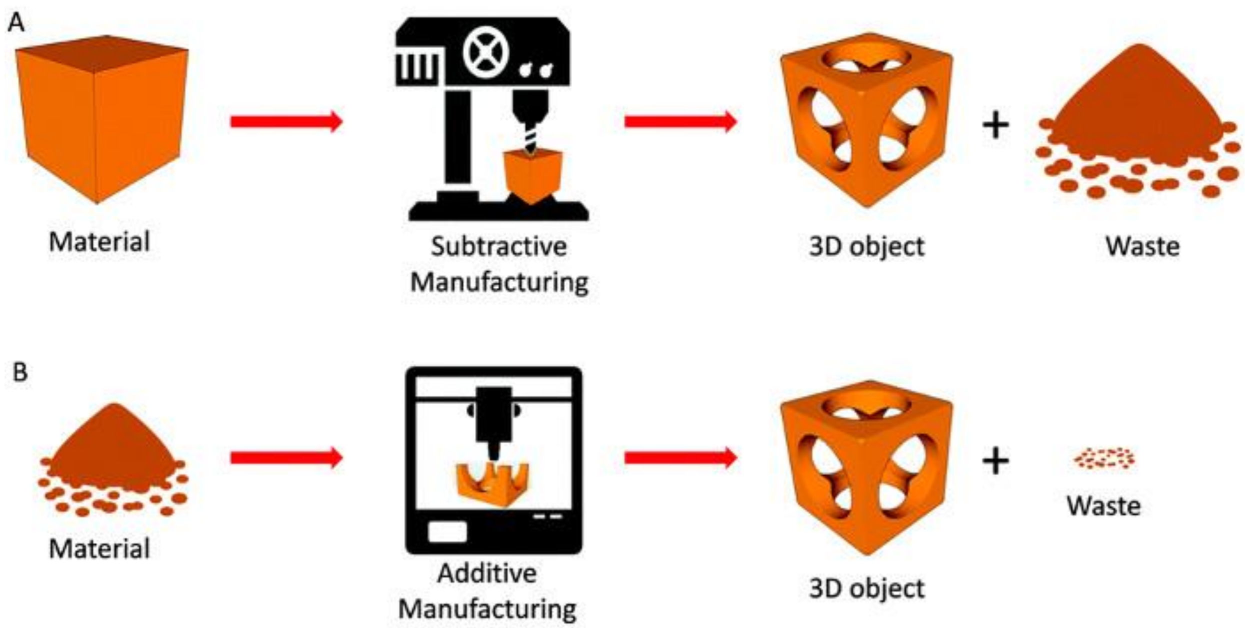

Figure 2.1: Manufacturing Process (3Dnatives, 2018).

Figure 2.1 on page 8 illustrates the difference in manufacturing processes and shows the potential for material waste. Additive manufacturing machines, 3D printers, can produce virtually any shape in a single print job (DebRoy et al., 2018). DebRoy explains, “Intricate parts, true to their design can be made in one-step without the limitations of conventional processing methods” (DebRoy et al., 2018, p. 115). The ability to print complex shapes can reduce part counts as an assembly can be printed as a single part (DebRoy et al., 2018). Three-dimensional printed parts can be produced on demand, reducing the need for inventory of spares and obsolete replacement components (DebRoy et al., 2018). Additive manufacturing is now accepted as “a new paradigm for the design and production of high-performance components for aerospace, medical, energy and automotive applications” (DebRoy et al., 2018, p. 115).

2.2 Additive Manufacturing Technologies

Today, there are many different additive manufacturing methods available. The additive manufacturing methods involve slicing the 3D CAD files and building a part layer by layer (Bikas et al., 2015). The additive manufacturing processes can be classified according to the type of material used and the delivery method (Abdulhameed et al., 2019). The raw material can start out in a solid, liquid, or powder form (Abdulhameed et al., 2019). Figure 2.2 on page 10 shows the different additive manufacturing processes.

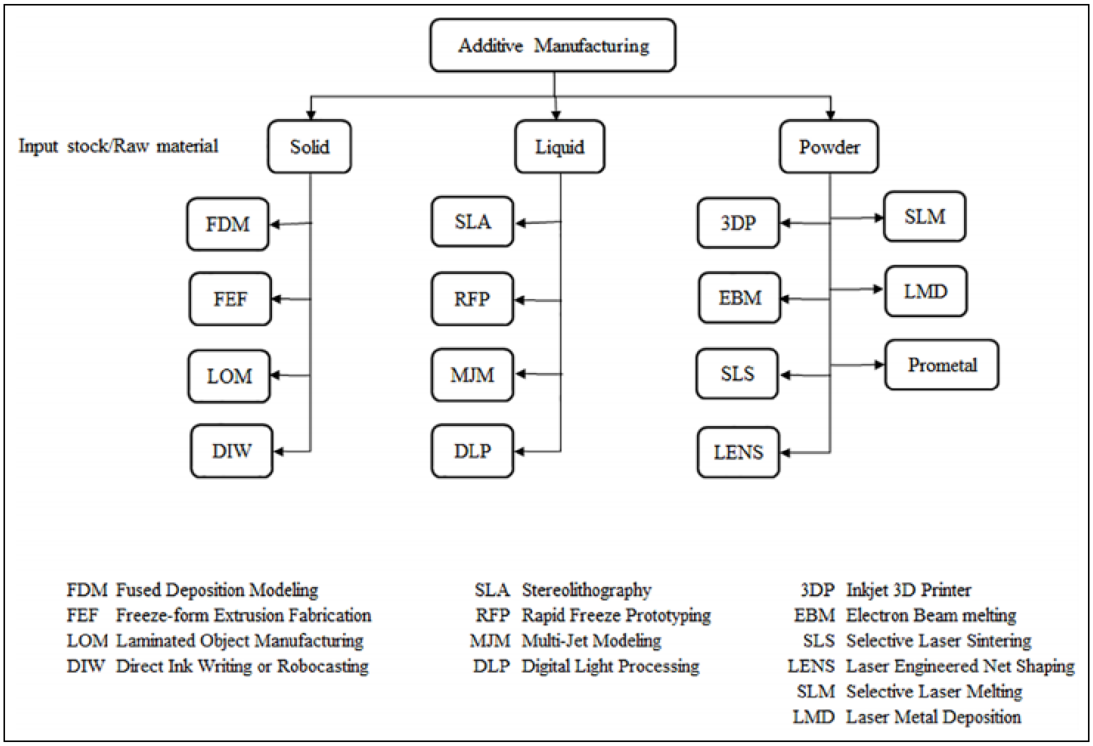

Figure 2.2: Additive Manufacturing Classification (Abdulhameed et al., 2019).

Figure 2.2 above, illustrates the classification of additive manufacturing processes based on the state of raw material. The various methods use materials such as plastic filaments, resins, or plastic or metal powders. The layers of printed materials are solidified to form the finished part using a laser or heated extruder as an energy source (3Dnatives, 2018).

2.2.1 Fused Deposition Modeling (FDM)

Fused deposition modeling (FDM) uses a continuous spool of thermoplastic polymer filament used to 3D print the layers (Ngo et al., 2018). The filament is heated in the nozzle to reach a liquid state and then extruded on top of previously printed layers (Ngo et al., 2018). On some machines the print head will contain two nozzles, one for the support material and one for the part material (Bikas et al., 2015). Certain part designs require the support material to provide a raised surface to build sequential layers with overhanging geometry. The common materials that are used in FDM are polyamide (PA), polycarbonate (PC), polyethylene (PE), acrylonitrile butadiene styrene (ABS), and polypropylene (PP) (Kumar et al., 2019). Fused deposition modeling is a low cost, high speed and relatively simple additive manufacturing process (Ngo et al., 2018). However, inter-layer distortion in the process may cause quality issues and mechanical weakness (Ngo et al., 2018). The accuracy, appearance, and surface quality of FDM are relatively poor when compared to powder-based plastic additive manufacturing processes (Bikas et al., 2015).

2.2.2 Stereolithography Apparatus (SLA)

One of the earliest methods of additive manufacturing, stereolithography, was developed in 1986 (Ngo et al., 2018). The stereolithography apparatus (SLA) machine converts liquid plastic raw material into solid objects (Palermo, 2013). “Stereolithography is based on the photopolymerization principle of photosensitive monomer resins when exposed to UV radiation” (Bikas et al., 2015, p. 390). The source of UV radiation is a low-power laser that solidifies a thin layer of material on the surface (Bikas et al., 2015). The SLA machine consists of a built platform, immersed into a bath of liquid resin, and a laser UV source (Bikas et al., 2015). The building platform moves the object down into the liquid bath as the layers are being made (Abdulhameed et al., 2019). Even though SLA builds the part in layers, the finished part is a solid piece of material. The solid parts produced in SLA have better strength and improved mechanical properties versus other methods of plastic additive manufacturing (Kumar et al., 2019). The improved strength makes SLA a cost-effective alternative to metal tool fabrication for low-volume mold tools (McGuigan, 2020). Stereolithography can create high-quality parts at a fine resolution, but it is relatively slow, expensive, and a very limited range of materials (Ngo et al., 2018).

2.2.3 Selective Laser Sintering (SLS)

Selective laser sintering (SLS) is a type of powder bed fusion that uses fine powder heated inside the printing machine (Ngo et al., 2018). A laser is then used to fuse the grains together (Bikas et al., 2015). The printer's build platform is heated just below the material's melt temperature to minimize thermal distortion and facilitate fusion with the layers (Bikas et al., 2015). The SLS method of additive manufacturing has large variety of material options, including polymers, metals, and alloy powders (Ngo et al., 2018). Unlike FDM and SLA, technologies such as SLS can build parts without any support structures, and eliminates the need for support material (3Dnatives, 2018). The main drawbacks of SLS are the slow process times, high costs and potential quality issues such as porosity (Ngo et al., 2018). The quality issues can occur from non-uniform heat distribution in the part, which can lead to thermal distortion and surface cracks (Bikas et al., 2015). Despite the drawbacks, "SLS's high degree of accuracy and surface quality renders it one of the most commonly used metal AM processes" (Bikas et al., 2015, p. 392).

2.2.4 Metal Binder Jetting

Metal Binder Jetting process uses a polymer binding agent to bind together metal powder (All3DP, 2020). Once the part is completed, the binding agent is burned away leaving only the metal material (All3DP, 2020). The material jetting process uses thin nozzles to spray an adhesive in order to bind the powder together into a solid object (Bikas et al., 2015). Binder Jetting is one of the more expensive and complicated methods as it requires multiple steps and machines (Ngo et al., 2018). First, the metal powder particles are bound together in the binding machine forming a “green state” object (All3DP, 2020). After the binding process, the object is removed from the powder and placed in a furnace to burn out the binder (All3DP, 2020). The printed object density is around 60% with voids throughout once the binder is removed (All3DP, 2020). Bronze can be used to infiltrate the object’s voids and increase the density to around 90%, resulting in greater strength (All3DP, 2020). The materials used in Metal Binder Jetting include metal powders of aluminum, stainless steel, and titanium (All3DP, 2020). The strength of Metal Binder Jetting is the ability to create strong and functional parts with complex geometry (All3DP, 2020). The small build sizes, high production costs, and process complexity may steer companies to focus on other additive manufacturing methods (All3DP, 2020).

2.3 Additive Manufacturing Materials

2.3.1 Polymers

Today, there is a wide variety of materials available for additive manufacturing applications. Polymers are the most common materials used in the 3D printing industry (Ngo et al., 2018). Polymers have a relatively high diversity among the different types and can be easily adopted in the different printing processes (Ngo et al., 2018). The common polymer materials used are polyamide, polycarbonate, polyethylene, ABS, and polypropylene (Kumar et al., 2019). Companies that manufacture 3D printers can also develop their own proprietary materials (Kumar et al., 2019). Additive manufacturing polymers are found in nearly every printing method in the form of thermoplastic filaments, resins or powders (Ngo et al., 2018).

2.3.2 Metal Alloys

Metal alloy technology is becoming a popular option in additive manufacturing (Ngo et al., 2018). The number of companies selling metal printing systems has grown every year since 2016 and will continue in the future (Ngo et al., 2018). Common metal alloys used in additive manufacturing include stainless steel, titanium, aluminum, nickel super alloys, and cobalt chrome (DebRoy et al., 2018). Unlike polymers, metal alloy printing has a limited number of technology options (Ngo et al., 2018). The most popular technology for printing metals is powder bed fusion and the relatively new method of binder jetting (Ngo et al., 2018).

2.3.3 Ceramics

Another growing technology is the use of ceramics in additive manufacturing (Ngo et al., 2018). Casting or machining ceramics can be difficult using traditional manufacturing methods (Eckel et al., 2016). Three-dimensional printing enables a major leap in ceramic geometrical flexibility (Eckel et al., 2016). Ceramic material can be printed on a variety of methods including SLS, SLA and Binder Jetting (Travitzky et al., 2014). Building a ceramic part layer by layer has the advantage of minimizing the amount of porosity (Ngo et al., 2018). Some of the printing methods can provide undesirable surface finishes. The disadvantage with ceramics is the difficulty to perform post printing operations to improve surface quality.

2.3.4 Biomedical

Additive manufacturing is not only used in the industrial sector, medical professionals use biomaterials to print skin, bone and cartilage, and prosthetics (Ngo et al., 2018). In 2018, the biomedical market represented 11% of the additive manufacturing market and will be one of the drivers for future growth (Ngo et al., 2018). Three-dimensional printing is a perfect option for biomedical applications, as they require complex geometry, patient-specific jobs, and small production quantities (Ngo et al., 2018). Biomedical printing involves biofabrication, which is “the generation of tissues and organs through bioprinting, bio-assembly and maturation” (Ngo et al., 2018, p. 182). The difference between conventional AM and biofabrication is the inclusion of cells with the biomaterials to produce artificial live tissue (Ngo et al., 2018).

2.4 Challenges

One of the main challenges of additive manufacturing is producing parts with the same strength and quality as traditional manufacturing methods. Traditional manufacturing consists of computer numerical control (CNC) machining and injection molding, and additive manufacturing uses 3D printing. The difference between 3D printing and CNC machining is that 3D printing is additive manufacturing, whilst CNC machining is subtractive (3Dnatives, 2018). Computer numerical control machining starts with a block of material, called a blank, and removes material to create the finished part (3Dnatives, 2018). Injection molding requires machining a mold with the parts shape and adding melted material to the mold. The following section will point out some of the differences between additive manufacturing, subtractive manufacturing, and injection molding.

Three-dimensional printing is a simple process to learn compared to CNC machining (3Dnatives, 2018). Once the 3D file is prepared, the part orientation is chosen, and the printer runs with no supervision. Depending on the technology, some post-processing may be required (3Dnatives, 2018). Three-dimensional printing may not be ideal for every part in an assembly, non-structural parts are typically easy targets (Markforged, n.d.). Structural parts that withstand significant physical loads should be produced with CNC machining or continuous fiber reinforcement (Markforged, n.d.). The advantage for CNC machining comes from part costs at high volumes (Markforged, n.d.). Most of the production cost comes from the time required for programming and setup; the time for actual machining is generally short (Markforged, n.d.). Scaling up production the volume can decrease the price per unit. The 3D printing programming and slicing usually happens in a matter of minutes, and complexity has little effect on the programming time (Markforged, n.d.). Scaling up the production in 3D printing typically has little effect on the price per unit (Markforged, n.d.). Unlike 3D printing, CNC machining is a far more labor-intensive process (3Dnatives, 2018). A skilled operator is required to choose between different tools, cutting speeds, cutting path, and repositioning as the part is being created (3Dnatives, 2018). Another advantage for CNC machines is the capability to control tighter part tolerances, as CNC machining can typically hold +/-0.025-0.125mm (3Dnatives, 2018). The tolerance varies among the different 3D printing technologies, SLS = +/-0.3mm, FDM = +/-0.5mm, DMLS = +/-0.1mm (3Dnatives, 2018). Features created in both CNC machining and 3D printing processes are constrained by the tooling size (Markforged, n.d.). The tool diameter used in CNC machining dictates the smallest negative feature size that can be created (Markforged, n.d.). The diameter of the nozzle used in 3D printing dictated the smallest positive feature size that can be produced (Markforged, n.d.).

Injection molding involves cutting the object's shape out of a block of material that can withstand high temperatures (Griffin, 2019). Molten build material is poured into the mold, and once the material has cooled in the mold, the finished part is ready (Griffin, 2019). Three-dimensional printing can save time and money, as tooling design is typically the most time-consuming and expensive part of the molding process (McGuigan, 2020). Three-dimensional printing is best suited for quick turnaround, low volume parts that may require frequent changes (McGuigan, 2020). Injection molding is best suited for the final design of high-volume parts (McGuigan, 2020). Three-dimensional printing can also simplify the process, as it only requires a 3D printer and the material (Griffin, 2019). Injection molding requires a molding machine, a specifically designed mold for the part, and material (Griffin, 2019). Additive manufacturing can also be used as a complementary technology to injection molding, instead of as a replacement (McGuigan, 2020). Prototypes can be created on 3D printers to shorten design and pre-production times (McGuigan, 2020). Three-dimensional printed molds in SLA material can also be used for low volume injection molding (McGuigan, 2020). The pros of 3D printing include low entry cost, easy to make changes, easy to support complicated designs. The cons of 3D printing include slower output versus molding, limited build volume, rough object surface. The pros of injection molding include large output, enhanced strength, minimal scrap. The cons of injection molding include limitations of design, difficult to make changes, high entry cost (Griffin, 2019).

CHAPTER 3. RESEARCH METHODOLOGY

3.1 Research Methodology Overview

Chapter Two, Review of Literature, highlighted the distinctions between the traditional and additive manufacturing processes. The differences in production cost, and material properties are assessed. The sample size includes four aerospace case study examples that used additive manufacturing to improve their process and part design. Product development lead time and flexibility on traditional manufacturing processes are falling behind the pace of technology innovation (Macleod, 2020). Additive manufacturing materials and equipment has evolved over the years to offer increased design freedom, reduced lead times, and less material waste (Bikas et al., 2015). The problem was measured by the reduction in manufacturing time, as high as 75% in some industries (Ngo et al., 2018).

3.1.1 Research Environment

The research environment for the research is specific to product manufacturing in the aerospace industry. The research environment also includes a high level of complexity in the part and assembly design. The desired outcome in the research environment is a cheaper, lighter design, with less parts and at a faster rate of production. The additive manufacturing part must also have the similar strength and reliability as the part machined using traditional manufacturing.

3.1.2 Sample Population

The research contains four separate case study examples of product manufacturing. All of the same participants are in the aerospace industry. All four examples used the same 3D printer, the Electro Optical Systems EOS M 400 direct laser sintering machine for industrial production (Electro Optical Systems, 2020b). The materials that used in the research vary among aluminum alloy, titanium alloy, and nickel-based alloy.

3.1.3 Statistical Measures

A hypothesis test was used to determine if there is a cost difference between additive and traditional manufacturing. The null hypothesis (H0) represents the skeptical perspective, and the alternative hypothesis (HA) represents an alternative claim based on various values (Diez et al., 2015). The hypothesis test will be:

H_0: There is no difference in manufacturing cost for traditional and additive manufacturing.

H_A: There is some difference in manufacturing cost for traditional and additive manufacturing.

3.1.4 Research Variables

The research variables for this study included independent variables and dependent variables. The independent variable for the research was the material used to create the printed part. All four examples used the same 3D printer, but the materials used vary among aluminum, titanium, and nickel-based alloys (Electro Optical Systems, 2020b). Another independent variable is the location of manufacturing. The dependent variables in this study were the production time, number of parts in final design, assembly weight, and production costs.

3.2 Research Instruments

The research instruments for determining the benefits of additive manufacturing come from a variety or resources. Details of the process improvements are given in the various case studies on the Electro Optical Systems (EOS) website (Electro Optical Systems, 2020a). The results listed in the case studies can include weight reduction, flexible production planning, design optimizations, and significant cost reductions (Electro Optical Systems, 2020a). The case studies provide historical process information, and the benefits of implementing additive manufacturing on the specific part.

The Electro Optical Systems (EOS) website provides the technical data for the 3D printer used in the four case studies (Electro Optical Systems, 2020b). The 3D printer is the EOS M 400 direct laser sintering machine for industrial production (Electro Optical Systems, 2020b). The technical data include the printer's build size and speed. The technical data also lists the available materials for the EOS M 400, including aluminum, steel, nickel alloy, and titanium (Electro Optical Systems, 2020b). A fundamental assumption is that 3D printed material, for example aluminum, will perform the same as a machined block of aluminum. Material data verification confirms that the additive manufacturing process is producing similar parts to traditional manufacturing.

3.3 Procedures for Data Collection

The procedures for data collection included four production part examples in the aerospace industry. All four examples used the same 3D printer, the EOS M 400, manufactured by Electro Optical Systems (EOS). The resources for data collection included case studies, material specifications, and manufacturing times and costs.

The first step in data collection was to identify the four examples of additive manufacturing implemented in the production process. Each of the four case study examples have their own specific challenge, or reason to investigate additive manufacturing. The cable routing bracket on the A350 XWB has a critical production lead time of only two weeks, including design and production (Electro Optical Systems, 2018a). The antenna bracket for Sentinel satellites has to be lightweight as well as robust to stabilize the antenna during a rocket launch (Electro Optical Systems, 2018b).The control hydraulic component on the Airbus A380 has to be lighter, resource-efficient, and eco-friendly, and fulfill all certification requirements for flight (Electro Optical Systems, 2018c). The injection head for rocket engines needs to be designed and produced with as few components as possible, while reducing the cost (Electro Optical Systems, 2019).

Once the four examples are identified, the next step was to gather the results. The case study results included reduction in weight, the number or parts, the production time, and the reduction in part cost. Next, the printed material was compared to the material used in traditional manufacturing to ensure the functionality of the printed part. Finally, the printer production time was compared to the traditional machine time. The reduction amount in production time was used to estimate the amount saved in production costs.

3.4 Presentation of Data

The presentation of data collection includes Tables and Figures to show the results for each example. The results data, and material specification data are presented in comparison tables. The comparison tables allow the reader to quickly see the difference between the manufacturing methods. A blank example of the results summary is shown in Table 3.1 on page 22.

Table 3.1: Example Results Summary

Example #		
Part		
Company		
	Traditional Manufactiuring	Additive Manufacturing
Material		
Production Time		
Number of Parts		
Assembly Weight		
Production Cost		

Table 3.1 above, shows an example layout of how the data will be presented. A table was created for each of the four case study examples. Figures are used to show an image of the manufactured parts, as shown in Figure 3.1 below.

Figure 3.1: Manufactured Part Image (Electro Optical Systems, 2018a)

Figure 3.1 on page 22 shows the initial components to be assembled from traditional manufacturing and the final printed part. Figure images of the examples allow the reader to see how the part or assembly has changed with the different manufacturing process. The material data from the manufacturing process is shown in tables, similar to Table 3.2 below.

Table 3.2: Material Comparison Summary

Material #		
	Traditional Manufactiuring	Additive Manufacturing
Material Spec		
Volume Rate (Print Speed)	cm^3/h	
Density	g/cm^3	
Tensile Strength	MPa	
Yield Strength	MPa	
Elongation @ Break	%	
Material Composition		
Al	wt%	
Si		
Fe		
Cu		
Mn		
Mg		
Ni		
Zn		
Pb		
Sn		
Ti		

Table 3.2 above, is an example layout of how the material data will be presented. A table was created for each material used in the four case study examples. The material data verifies the assumption that a printed part will perform the same as one created in traditional manufacturing.

The following physical and mechanical properties were compared; density, yield strength, ultimate tensile strength, and elongation at break. The density is used to describe the mass of the material (Olsen, 2020). Density will be presented as the material weight (grams) per unit volume (cubic centimeter). Yield strength describes the load point when the material will no longer return to its original shape (Olsen, 2020). Ultimate tensile strength refers to the amount of load the metal can withstand before it breaks (Olsen, 2020). Yield strength and ultimate tensile strength will be presented in megapascal (MPa). Elongation at break describes the ductility of a material, or the amount of deformation (Olsen, 2020). Elongation at break will be presented in a ratio (%) of changed length and initial length after breakage.

3.5 Return on Investment

Calculating the return on investment (ROI) provides insight into the real value for a company after the adoption of new processes (Oyesola, et al., 2019). The ROI formula that was used to determine the payback of additive manufacturing is shown in Figure 3.2 below.

$$\text{ROI} = \left(\frac{\text{Total Cost of Printer}}{\text{(Tra-Man. Part Cost - Add-Man. Part Cost)}} \right) / \left(\frac{\text{Total Production Time}}{\text{Part Print time}} \right)$$

$$\text{ROI} = \left(\text{Parts to Achieve ROI} \right) / \left(\text{Parts Per Week} \right)$$

Figure 3.2: Return on Investment Formula (Markforged, 2021b)

Figure 3.2 above, shows the ROI has been calculated by dividing parts to achieve ROI by the number of parts per week (Markforged, 2021b). The number of parts to achieve ROI was determined by dividing the cost of the printer by the additive manufacturing cost savings (Markforged, 2021b). The number of parts per week was determined by dividing the weekly production time by the specific parts print time (Markforged, 2021b). The ROI provides a timeframe used to evaluate the efficiency of the process investment (Brundage et al., 2015). The cost of manufacturing was calculated for both traditional and additive manufacturing to determine the cost gain from the investment. It is necessary to determine the costs from raw material to production and through the shipping of the final product (Thomas & Gilbert, 2015). The formula to calculate the cost of traditional manufacturing is shown in Figure 3.3 below

$$C_{Trad} = \left(MI_{R,Trad} + MI_{I,Trad} + MI_{A,Trad}\right) + \left(P_{E,Trad} + P_{R,Trad} + P_{I,Trad} + P_{A,Trad}\right) + \left(FGI_{E,Trad} + FGI_{R,Trad} + FGI_{I,Trad} + FGI_{A,Trad}\right) + WT_{Trad} + RT_{Trad} + T_{Trad}$$

Where

C_{Trad} = Cost of producing a product using traditional processes ($Trad$)

MI = Cost of material inventory for refining raw materials (R), producing intermediate goods (I), and assembly (A) for traditional manufacturing ($Trad$)

P = Cost of the process of material extraction (E), refining raw materials (R), producing intermediate goods (I), and assembly (A), including administrative costs, machine costs, and other relevant costs for traditional manufacturing ($Trad$)

FGI = Cost of finished goods inventory for material extraction (E), refining raw materials (R), producing intermediate goods (I), and assembly (A) for traditional manufacturing ($Trad$)

WT_{Trad} = Cost of wholesale trade for traditional manufacturing ($Trad$)

RT_{Trad} = Cost of retail trade for traditional manufacturing ($Trad$)

T_{Trad} = Transportation costs throughout the supply chain for a product made using traditional manufacturing ($Trad$)

Figure 3.3: Cost of Traditional Manufacturing Formula (Thomas & Gilbert, 2015)

Figure 3.3 above, shows an example formula to determine the cost of traditional manufacturing. The formula to calculate the cost of additive manufacturing is shown in Figure 3.4 on page 26

$$C_{AM} = (MI_{R,AM} + MI_{M,AM}) + (P_{E,AM} + P_{R,AM} + P_{M,AM}) + (FGI_{E,AM} + FGI_{R,AM} + FGI_{M,AM}) + WT_{AM} + RT_{AM} + T_{AM}$$

Where
C_{AM} = Cost of producing an additive manufactured product
MI = Cost of material inventory for refining raw materials (R) and for manufacturing (M) for additive manufacturing (AM)
P = Cost of the process of material extraction (E), refining raw materials (R), and manufacturing (M), including administrative costs, machine costs, and other relevant costs for additive manufacturing (AM)
FGI = Cost of finished goods inventory for material extraction (E), refining raw materials (R), and manufacturing (M) for additive manufacturing (AM)
WT_{AM} = Cost of wholesale trade for additive manufacturing (AM)
RT_{AM} = Cost of retail trade for additive manufacturing (AM)
T_{AM} = Transportation cost throughout the supply chain for an additive manufactured Product (AM)

Figure 3.4: Cost of Additive Manufacturing Formula (Thomas & Gilbert, 2015)

Figure 3.4 above, shows an example formula to determine the cost of additive manufacturing. The difference between the two costs of manufacturing from Figure 3.3 and Figure 3.4 is the amount of gain from investment. Some of the information for the cost of manufacturing formulas is not readily available, so there are some assumptions. Research assumptions that can be used include production quantity, warehouse time and cost, retail costs, and transportation cost.

3.6 Research Methodology Summary

The research methodology presented in Chapter Three includes the research measurements, data collection procedures, presentation of data, and the return on investment. The research instruments include case study examples, 3D printer technical data, and material data. Data collection starts with identifying the four examples, gathering the results, collecting material properties, and collecting manufacturing production data. The data is presented in Tables to compare the manufacturing process, and material data. Figures are also provided for a visual observation to differences in manufacturing processes. Finally, the return on investment formula was presented, along with the formulas to determine the cost of the two manufacturing processes. The next chapter will present the data, results, and calculations for the material and processes used in both traditional and additive manufacturing.

CHAPTER 4. RESULTS

4.1 Introduction

Chapter Three, Research Methodology, explained the process and tools to gather the research results for both traditional and additive manufacturing. The research results illustrate the difference between traditional and additive manufacturing costs. While the material properties and compositions are similar between traditional and additive manufacturing, the production time and cost varied significantly. Chapter Four will present the research and results of the four separate case study examples of product manufacturing in the aerospace industry. The four examples all use the same 3D printer, the Electro Optical Systems EOS M 400 direct laser sintering machine for industrial production (Electro Optical Systems, 2020b). The materials that are used in the results vary among aluminum alloy, titanium alloy, and nickel-based alloy.

Product development lead time and flexibility on traditional manufacturing processes are falling behind the pace of technology innovation (Macleod, 2020). Additive manufacturing materials and equipment has evolved over the years to offer increased design freedom, reduced lead times, and less material waste (Bikas et al., 2015). The problem can be measured by the reduction in manufacturing time, as high as 75% in some industries (Ngo et al., 2018). Additive manufacturing increases the availability for critical parts and tools of scientific discovery (National Academy of Engineering, n.d.b). A hypothesis test was used to determine if there is a cost difference between additive and traditional manufacturing.

4.2 Results Background

The four case study results all use the same 3D printer, the Electro Optical Systems EOS M 400 direct laser sintering machine (Electro Optical Systems, 2020b). The cost of the printer includes the sale price, as well as costs for repairs and upgrades throughout the machine's life. The summary of the total cost calculation for the EOS M 400 3D printer is shown in Table 4.1 below.

Table 4.1: Total Cost of EOS M 400 Printer

Cost of Printer: EOS M 400	750,000.00
Annual Maintenance (10%)	75,000.00
Printer Life Expectancy (years)	10.00
Total Cost of Printer	1,500,000.00

Table 4.1 above, shows the estimated total cost of the EOS M 400 is $1,500,000.00. The average purchase price of the EOS M 400 3D printer is $750,000.00 (Treatstock, 2021). Three-dimensional printer manufactures recommend planning to spend ten percent of the printer's cost annually to account for repairs and upgrades (3DSourced, 2020). The estimated life expectancy of a 3D printer is ten years with proper use and maintenance (Dwamena, 2021). The total cost of the EOS M 400 and life expectancy will be used to estimate the production cost for additive manufacturing (3DSourced, 2020). The hourly production cost will be used to estimate the additive manufacturing part cost. The summary of the production cost for additive manufacturing is shown in Table 4.2 on page 30.

Table 4.2: Additive Manufacturing Production Cost

Printer Life Expectancy (years)	10
Weeks/Year	52
Working Days/Week	5
Printer Working Hours/Day	24
Total Operating Hours	62400
Total Cost of Printer ($)	1500000.00
Hourly Production Cost ($)	*24.04*

Table 4.2 above, shows the estimated production cost of the 3D printer is $24.04 per hour. The assumption is that the machine can operate 24 hours in a day for five working days per week. The production cost for traditional manufacturing will be based on average machine shop cost. The average U.S. machine shop rate is 60 to 80 dollars per hour (CNC Machinist Training, 2021). The traditional manufacturing production cost used in each case study will be $80 per hour. The first part of determining the return on investment (ROI) is to calculate the number of parts to achieve the payback period (Markforged, 2021b). The cost of additive manufacturing is subtracted from the cost of traditional manufacturing to calculate the per part savings (Markforged, 2021b). The total cost of the printer divided by the pert part savings equals the number of parts to achieve ROI payback (Markforged, 2021b). The number of parts for ROI payback and production time were used to calculate the ROI timeframe for each case study.

4.3 Case Study One: A350 XWB Cable Routing Bracket

The first case study was the A350 XWB cable mounting bracket manufactured by Sogeti High Tech. The bracket is needed for the power supply and data transportation of a camera located in the vertical stabilizer (Electro Optical Systems, 2018a). Sogeti High Tech is a subsidiary of Cap Gemini, and a center of excellence for systems engineering, physical engineering, and software engineering (Electro Optical Systems, 2018a). The cable routing bracket on the A350 XWB has a critical production lead time of only two weeks, including design and production (Electro Optical Systems, 2018a). A summary of the production results is shown in Table 4.3 below.

Table 4.3: Case Study #1 Production Results

Case Study #1		
Part	A350 XWB Cable Routing Bracket	
Company	Sogeti High Tech, Airbus	
	Traditional Manufacturing	Additive Manufacturing
Material	2024-T3 Alclad Aluminum	EOS Aluminum AlSi10Mg
Production Time	*70 days (560 hours)*	19 hours
Number of Parts	30	1
Assembly Weight	452 g	317 g

Table 4.3 above, shows the component differences from traditional and additive manufacturing. The traditional manufacturing produced component was made up of the formed sheet metal parts and mounting hardware, totaling 30 individual parts (Electro Optical Systems, 2018a). The total production time for the traditional manufacturing part was 70 days, and the finished assembly weighed 452 grams (Electro Optical Systems, 2018a). A visual of the cable routing bracket is shown in Figure 4.1 on page 32.

Figure 4.1: A350 XWB Cable Routing Bracket (Electro Optical Systems, 2018a).

Figure 4.1 above, shows the components that go into the traditional manufacturing bracket on the right. The single additive manufacturing produced part is shown in the lower left corner. The additive manufacturing produced part was completed in 19 hours, with a final weight of 317 grams (Electro Optical Systems, 2018a). The mounting hardware was integrated into the bracket design, reducing the part count to a single component (Electro Optical Systems, 2018a).

The material used on the additive manufacturing component is the proprietary aluminum powder AlSi10Mg (Electro Optical Systems, 2018a). Electro Optical System's Aluminum AlSi10Mg offers good strength, hardness and mechanical properties and is ideal for thin complex structures (Electro Optical Systems, 2021a). The material used in the traditional manufacturing part was not available, so an assumption is made. Alclad aluminum 2024-T3 is one of the most common aluminum alloys used in aircraft construction (Alexander, 1997).

The cost of material was determined based on estimates from material suppliers and similar machines. Aircraft quality aluminum 2024 T3 sheets costs from $3.99/sq-ft for 0.020" thickness up to \$10.78/sq-ft for 0.063” thickness (Aluminum Supply Inc, 2021). A summary of the average price for aluminum 2024 T3 is shown in Table 4.4 below.

Table 4.4: Aluminum 2024 T3 Average Sheet Price

Aluminum Sheet						
$/sq-ft	3.99	4.98	4.38	7.49	8.56	10.78
Thickness (Inch)	0.020	0.025	0.032	0.040	0.050	0.063
Thickness (CM)	0.05	0.06	0.08	0.10	0.13	0.16
Length (Inch)	12.00	12.00	12.00	12.00	12.00	12.00
Length (CM)	30.48	30.48	30.48	30.48	30.48	30.48
Width (Inch)	12.00	12.00	12.00	12.00	12.00	12.00
Width (CM)	30.48	30.48	30.48	30.48	30.48	30.48
Volume (cm^3)	47.19	58.99	75.51	94.39	117.99	148.66
Density (g/cm^3)	2.78	2.78	2.78	2.78	2.78	2.78
Material Weight / sq-ft (g)	131.20	164.00	209.92	262.40	328.00	413.28
Material Price ($/g)	0.030	0.030	0.021	0.029	0.026	0.026
Average Price ($/g)	***0.027***					

Table 4.4 above, shows the average price for Aluminum 2024 T3 is \$0.027 per gram. The average price was calculated from the price per square foot divided by the weight of a square foot. The material weight was calculated by multiplying the volume of a square foot and the material’s density property. Since the cost of EOS material is not readily available, another assumption is made. Metal printing powders are typically between \$350 and \$550 per kg (Gregurić, 2019). The assumption for the EOS Aluminum AlSi10Mg cost is \$500 per kg, or \$0.50 per gram. The calculation for the traditional manufacturing part cost is shown in Table 4.5 on page 34.

Table 4.5: Case Study #1 Traditional Manufacturing Part Cost

C_Traditional Manufacturing	**Case Study #1**
Material Cost per g	0.027
Part Weight (g)	452
Material Cost, Part (MI_Trad)	12.23
Production Cost per hour	80
Productuon time (hours)	560
Production Cost (P_Trad)	44800.00
Part Cost (C_Trad)	44812.23

Table 4.5 above, shows the estimated cost of traditional manufacturing for the cable routing bracket is $44,812.23 per part. The part cost is a total of $12.23 in material and $44,800.00 in production cost. The calculations for the additive manufacturing part cost is shown in Table 4.6 below.

Table 4.6: Case Study #1 Additive Manufacturing Part Cost

C_Additive Manufacturing	**Case Study #1**
Material Cost per g	0.5
Part Weight (g)	317
Material Cost (MI_AM)	158.50
Production Cost per hour	24.04
Productuon time (hours)	19
Production Cost (P_AM)	456.73
Part Cost (C_AM)	615.23

Table 4.6 above, shows the estimated cost of additive manufacturing for the cable routing bracket is $615.23 per part. The part cost is a total of $158.50 in material and $456.73 in production cost. The difference in the two manufacturing costs was used to calculate the per part

savings to determine the return on investment (ROI). A summary of the ROI calculation is shown in Table 4.7 below.

Table 4.7: Case Study #1 Return on Investment

	Case Study #1
Per Part Savings	44197.00
Cost of Printer: EOS M 400	1500000.00
Parts to Achieve ROI	33.94
Print Time (hours)	19
Production Time (hours/week)	120
Parts Per Week	6.3
Weeks to Achieve ROI	5.37

Table 4.7 above, shows the time to achieve the return on investment (ROI) payback is just over five weeks. The per part savings is the difference between the parts costs for traditional and additive manufacturing. The cost of the printer divided by the per part savings equals the total number of parts to achieve the ROI payback. Since the printer can run unmonitored overnight, the production time is 24 hours per day for five working days per week. At 19 hours per part, 6.3 parts can be produced per week. 33.94 parts are required to achieve the ROI, at 6.3 parts per week equals 5.37 week for the payback period.

The next step was to compare the mechanical properties of the additive manufacturing material to the Alclad Aluminum 2024-T3. The material used on the additive manufacturing component is the EOS Aluminum AlSi10Mg (Electro Optical Systems, 2018a). A summary of the material properties and composition is shown in Table 4.8 on page 36.

Table 4.8: Case Study #1 Material Properties and Composition

Material #1 Aluminum		
	Traditional Manufacturing	**Additive Manufacturing**
Material Spec	**2024-T3 Alclad Aluminum**	**EOS Aluminum AlSi10Mg**
Density (g/cm^3)	2.78	2.64
Ultimate Tensile Strength (MPa)	448	395
Yield Strength (MPa)	310	244
Elongation @ Break (%)	10	5
Material Composition	**2024-T3 Alclad Aluminum**	**EOS Aluminum AlSi10Mg**
Aluminum (Al)	90.7 - 94.7 %	Balance
Chromium (Cr)	<= 0.10 %	---
Copper (Cu)	3.8 - 4.9 %	<= 0.05 %
Iron (Fe)	<= 0.50 %	<= 0.55 %
Magnesium (Mg)	1.2 - 1.8 %	0.20- 0.45 %
Manganese (Mn)	0.30 - 0.90 %	<= 0.45 %
Other, each	<= 0.05 %	<= 0.05 %
Other, total	<= 0.15 %	<= 0.15 %
Silicon (Si)	<= 0.50 %	9.0 - 11.0 %
Titanium (Ti)	<= 0.15 %	<= 0.15 %
Zinc (Zn)	<= 0.25 %	<= 0.10 %
Nickel (Ni)	---	<= 0.05 %
Lead (Pb)	---	<= 0.05 %
Tin (Sn)	---	<= 0.05 %

Table 4.8 above, shows the similarities of the printed EOS Aluminum AlSi10Mg and the Alclad Aluminum 2024-T3. Alclad Aluminum 2024-T3 has a density of 2.78 g/cm3 (MatWeb, 2021a). Electro Optical Systems Aluminum AlSi10Mg has a density of 2.64 g/cm3 (Electro Optical Systems, 2018d). Alclad Aluminum 2024-T3 has an ultimate tensile strength of 448 MPa, yield strength of 310 MPa and elongation at break of 10% (MatWeb, 2021a). EOS Aluminum AlSi10Mg has an ultimate tensile strength of 395 MPa, and yield strength of 244 MPa (Electro Optical Systems, 2018d). Electro Optical Systems Aluminum AlSi10Mg has an elongation at break of 5% (Electro Optical Systems, 2021a).

4.4 Case Study Two: Sentinel Satellite Antenna Bracket

The second case study was the Sentinel satellite antenna bracket manufactured by RUAG Holding (Electro Optical Systems, 2018b). The satellite bracket experiences extreme vibrations and forces during a rocket launch resulting in high stability and rigidity requirements (Electro Optical Systems, 2018b). A summary of the production results is shown in Table 4.9 below.

Table 4.9: Case Study #2 Production Results

Case Study #2		
Part	Sentinel Satellite Antenna Bracket	
Company	RUAG Holding	
	Traditional Manufacturing	Additive Manufacturing
Material	2024-T3 Alclad Aluminum	EOS Aluminum AlSi10Mg
Production Time	*500 hours*	80 hours
Assembly Weight	1600 g	940 g

Table 4.9 above, shows the component differences from traditional and additive manufacturing. The traditional manufacturing produced component was made up of a formed sheet metal part (Electro Optical Systems, 2018b). The total production time for the traditional manufacturing part was 500 hours, and the finished assembly weighed 1600 grams (Electro Optical Systems, 2018b). The additive manufacturing produced part was completed in 80 hours, with a final weight of 940 grams (Electro Optical Systems, 2018b). The satellite bracket was redesigned for the additive manufacturing process to produce a more complex shape (Electro Optical Systems, 2018b). A visual of the satellite bracket redesign process is shown in Figure 4.2 on page 38.

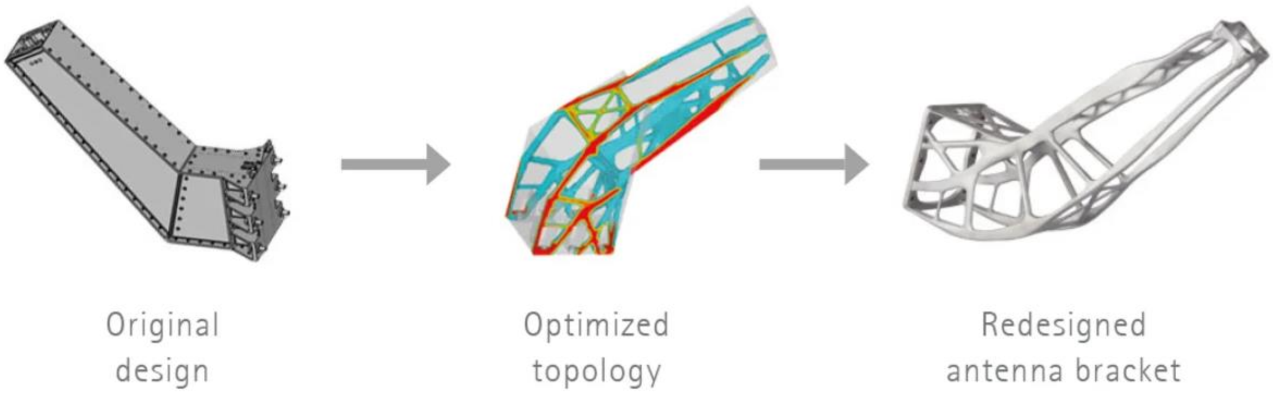

Figure 4.2: Sentinel Satellite Antenna Bracket Redesign (Electro Optical Systems, 2018b).

Figure 4.2 above, shows the traditional manufacturing sheet metal design, and the complex redesign for additive manufacturing. The new bracket design exceeded minimum rigidity requirements by more than 30%, with a highly uniform stress distribution (Electro Optical Systems, 2018b).

The materials used on the satellite bracket in case study #2 are the same as used in case study #1. The assumption for the EOS Aluminum AlSi10Mg cost is $500 per kg, or $0.50 per gram. The average price for Aluminum 2024 T3 is $0.027 per gram (Aluminum Supply Inc, 2021). The calculation for the cost of traditional manufacturing is shown in Table 4.10 on page 39.

Table 4.10: Case Study #2 Traditional Manufacturing Part Cost

C_Traditional Manufacturing	**Case Study #2**
Material Cost per g	0.027
Part Weight (g)	1600
Material Cost, Part (MI_Trad)	43.30
Production Cost per hour	80
Productuon time (hours)	500
Production Cost (P_Trad)	40000.00
Part Cost (C_Trad)	40043.30

Table 4.10 above, shows the estimated cost of traditional manufacturing for the satellite antenna bracket is $40,043.30 per part. The part cost is a total of $43.30 in material and $40,000.00 in production cost. The calculation for the cost of additive manufacturing is shown in Table 4.11 below.

Table 4.11: Case Study #2 Additive Manufacturing Part Cost

C_Additive Manufacturing	**Case Study #2**
Material Cost per g	0.5
Part Weight (g)	940
Material Cost (MI_AM)	470.00
Production Cost per hour	24.04
Productuon time (hours)	80
Production Cost (P_AM)	1923.08
Part Cost (C_AM)	2393.08

Table 4.11 above, shows the estimated cost of additive manufacturing for the cable routing bracket is $2,393.08 per part. The part cost is a total of $470.00 in material and $1,923.08 in production cost. The difference in the two manufacturing costs was used to calculate the per part savings to determine the return on investment (ROI). A summary of the ROI calculation is shown in Table 4.12 on page 40.

Table 4.12: Case Study #2 Return on Investment

	Case Study #2
Per Part Savings	37650.22
Cost of Printer: EOS M 400	1500000.00
Parts to Achieve ROI	39.84
Print Time (hours)	80
Production Time (hours/week)	120
Parts Per Week	1.5
Weeks to Achieve ROI	26.56

Table 4.12 above, shows the time to achieve the return on investment (ROI) payback is 26.56 weeks. The per part savings is the difference between the parts costs for traditional and additive manufacturing. The cost of the printer divided by the per part savings equals the total number of parts to achieve the ROI payback. Since the printer can run unmonitored overnight, the production time is 24 hours per day for five working days per week. At 80 hours per part, 1.5 parts can be produced per week. 39.84 parts are required to achieve the ROI, at 1.5 parts per week equals 26.56 week for the payback period.

4.5 Case Study Three: Airbus A380 Primary Flight Control Hydraulic Component

The third case study was the primary flight control hydraulic component manufactured by Liebherr-Aerospace. The component is a high-pressure hydraulic valve block with high standards of quality and precision (Electro Optical Systems, 2018c). The control hydraulic component on the Airbus A380 must be lighter, resource-efficient, and eco-friendly, and fulfill all certification requirements for flight (Electro Optical Systems, 2018c). A summary of the production results is shown in Table 4.13 on page 41.

Table 4.13: Case Study #3 Production Results

Case Study #3		
Part	Airbus A380 Primary Flight Control Hydraulic Component	
Company	Liebherr-Aerospace, Airbus	
	Traditional Manufacturing	Additive Manufacturing
Material	Titanium Ti-6Al-4V (Grade 5), Annealed	EOS Titanium Alloy (Ti64)
Production Time	4 days	1 day
Assembly Weight	*1000 g*	*650 g*

Table 4.13 above, shows the component differences from traditional and additive manufacturing. The traditional manufacturing produced component was made up of forged raw material that is machined and drilled to the final specifications (Electro Optical Systems, 2018c). The total production time for the traditional manufacturing part was four days, and just one day for additive manufacturing (Electro Optical Systems, 2018c). A visual of the primary flight control hydraulic component is shown in Figure 4.3 below.

Figure 4.3: Control Hydraulic Component (Electro Optical Systems, 2018c).

Figure 4.3 on page 41 shows the complex additive manufacturing produced component. The additive manufacturing process was able to eliminate 10 parts for the product design (Electro Optical Systems, 2018c). Due to product confidentiality, the weight was not given, but the case study mentions a 35% reduction in weight for additive manufacturing (Electro Optical Systems, 2018c). An assumption will be used for the part weight at 1000 grams for the traditional manufactured part. The additive manufactured part will be 35% less at 650 grams

The material used on the additive manufacturing component was the proprietary titanium powder Ti64 (Electro Optical Systems, 2018c). Electro Optical Systems Titanium Ti64 is a light alloy characterized by excellent mechanical properties and corrosion resistance, with low specific weight (Electro Optical Systems, 2021c). The material used in the traditional manufacturing part was not available, so an assumption is made. Titanium aluminide Ti-6Al-4V is a popular material choice for the aerospace industry that has been around since the 1970s (Standridge, 2014).

The cost of material was determined based on estimates from material suppliers and similar machines. Alpha-Beta titanium aluminide alloy Ti-6Al-4V grade 5 one-inch diameter bar varies in price from $48.84 up to $256.08 depending on the length (Titanium Processing Center, 2021a). Alpha-Beta titanium aluminide alloy Ti-6Al-4V grade 5 two-inch diameter bar varies in price from $99.93 up to $861.97 depending on the length (Titanium Processing Center, 2021b). A summary of the average price for Titanium aluminide Ti-6Al-4V is shown in Table 4.14 on page 43.

Table 4.14: Titanium Ti64 Average Bar Price

Titanium Bar-2"								
$/bar	99.93	168.66	237.99	307.32	445.99	584.65	723.31	861.97
Length (Inch)	6.00	12.00	18.00	24.00	36.00	48.00	60.00	72.00
Length (CM)	15.24	30.48	45.72	60.96	91.44	121.92	152.40	182.88
Diameter (Inch)	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Diameter (CM)	5.08	5.08	5.08	5.08	5.08	5.08	5.08	5.08
Volume (cm^3)	308.89	617.78	926.67	1235.56	1853.33	2471.11	3088.89	3706.67
Density (g/cm^3)	4.43	4.43	4.43	4.43	4.43	4.43	4.43	4.43
Material Weight (g/bar)	1368.38	2736.76	4105.13	5473.51	8210.27	10947.02	13683.78	16420.53
Material Price ($/g)	0.07	0.06	0.06	0.06	0.05	0.05	0.05	0.05
Titanium Bar-1"								
$/bar	48.84	67.68	86.52	105.36	143.04	180.72	218.40	256.08
Length (Inch)	6.00	12.00	18.00	24.00	36.00	48.00	60.00	72.00
Length (CM)	15.24	30.48	45.72	60.96	91.44	121.92	152.40	182.88
Diameter (Inch)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Diameter (CM)	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54
Volume (cm^3)	77.22	154.44	231.67	308.89	463.33	617.78	772.22	926.67
Density (g/cm^3)	4.43	4.43	4.43	4.43	4.43	4.43	4.43	4.43
Material Weight (g/bar)	342.09	684.19	1026.28	1368.38	2052.57	2736.76	3420.94	4105.13
Material Price ($/g)	0.14	0.10	0.08	0.08	0.07	0.07	0.06	0.06
Average Price ($/g)	***0.070***							

Table 4.14 above, shows the average price for Titanium aluminide Ti-6Al-4V is $0.070 per gram. The average price was calculated from the price per bar divided by the weight of the bar. The material weight was calculated by multiplying the volume of a bar and the material's density property. Since the cost of EOS material is not readily available, another assumption is made. Similar metal printing powders from Markforged range from $0.65 to $1.65 per gram (Markforged, 2021a). The assumption for the EOS Titanium Ti64 cost will be $1.15 per gram. The calculation for the cost of traditional manufacturing is shown in Table 4.15 on page 44.

Table 4.15: Case Study #3 Traditional Manufacturing Part Cost

C_Traditional Manufacturing	**Case Study #3**
Material Cost per g	0.070
Part Weight (g)	1000
Material Cost, Part (MI_Trad)	70.42
Production Cost per hour	80
Productuon time (hours)	32
Production Cost (P_Trad)	2560.00
Part Cost (C_Trad)	2630.42

Table 4.15 above, shows the estimated cost of traditional manufacturing for the control hydraulic component is $2630.42 per part. The part cost is a total of $70.42 in material and $2560.00 in production cost. The calculation for the cost of additive manufacturing is shown in Table 4.16 below.

Table 4.16: Case Study #3 Additive Manufacturing Part Cost

C_Additive Manufacturing	**Case Study #3**
Material Cost per g	1.15
Part Weight (g)	650
Material Cost (MI_AM)	747.50
Production Cost per hour	24.04
Productuon time (hours)	8
Production Cost (P_AM)	192.31
Part Cost (C_AM)	939.81

Table 4.16 above, shows the estimated cost of additive manufacturing for the control hydraulic component is $939.81 per part. The part cost is a total of $747.50 in material and $192.31 in production cost. The difference in the two manufacturing costs is used to calculate the

per part savings to determine the return on investment (ROI). A summary of the ROI calculation is shown in Table 4.17 below.

Table 4.17: Case Study #3 Return on Investment

	Case Study #3
Per Part Savings	1690.62
Cost of Printer: EOS M 400	1500000.00
Parts to Achieve ROI	887.25
Print Time (hours)	8
Production Time (hours/week)	120
Parts Per Week	15.0
Weeks to Achieve ROI	59.15

Table 4.17 above, shows the time to achieve the return on investment (ROI) payback is 59.15 weeks. The per part savings is the difference between the parts costs for traditional and additive manufacturing. The cost of the printer divided by the per part savings equals the total number of parts to achieve the ROI payback. Since the printer can run unmonitored overnight, the production time is 24 hours per day for five working days per week. At eight hours per part, 15 parts can be produced per week. 887.25 parts are required to achieve the ROI, at 15 parts per week equals 59.15 week for the payback period.

The next step was to compare the mechanical properties of the additive manufacturing material to the Titanium Ti-6Al-4V (grade 5), annealed. The material used on the additive manufacturing component is the EOS Titanium Alloy Ti64 (Electro Optical Systems, 2018c). A summary of the material properties and composition is shown in Table 4.18 on page 46.

Table 4.18: Case Study #3 Material Properties and Composition

Material #2 Titanium Alloy		
	Traditional Manufacturing	**Additive Manufacturing**
Material Spec	**Titanium Ti-6Al-4V (Grade 5), Annealed**	**EOS Titanium Alloy (Ti64)**
Density (g/cm^3)	4.43	4.4
Ultimate Tensile Strength (MPa)	950	1040
Yield Strength (MPa)	880	930
Elongation @ Break (%)	14	14
Material Composition	**Titanium Ti-6Al-4V (Grade 5), Annealed**	**EOS Titanium Alloy (Ti64)**
Aluminum (Al)	5.5 - 6.75 %	5.5 - 6.75 %
Carbon (C)	<= 0.080 %	<= 0.080 %
Hydrogen (H)	<= 0.015 %	<= 0.015 %
Iron (Fe)	<= 0.40 %	<= 0.30 %
Nitrogen (N)	<= 0.030 %	<= 0.050 %
Other, each	<= 0.050 %	<= 0.10 %
Other, total	<= 0.30 %	<= 0.40 %
Oxygen (O)	<= 0.20 %	<= 0.20 %
Titanium (Ti)	87.725 - 91 %	Balance
Vanadium (V)	3.5 - 4.5 %	3.5 - 4.5 %

Table 4.18 above, shows the similarities of the printed EOS Titanium Alloy Ti64 and the Titanium Ti-6Al-4V (grade 5), annealed. Titanium Ti-6Al-4V (grade 5), annealed has a density of 4.43 g/cm3 (MatWeb, 2021c). Electro Optical Systems Titanium Alloy Ti64 heat treated has a density of 4.4 g/cm3 (Electro Optical Systems, 2017). Titanium Ti-6Al-4V has an ultimate tensile strength of 950 MPa, yield strength of 880 MPa and elongation at break of 14% (MatWeb, 2021c). Electro Optical Systems Titanium Ti64 has an ultimate tensile strength of 1040 MPa, yield strength of 930 MPa and elongation of 14% (Electro Optical Systems, 2017).

4.6 Case Study Four: Rocket Engine Injector Head

The fourth case study was the rocket engine injector head manufactured by ArianeGroup. The injector head is used in a propulsion module that experiences tremendous forces under extreme conditions (Electro Optical Systems, 2019). The goal of the ArianeGroup was to produce an injection head with as few parts as possible and lower unit costs (Electro Optical Systems, 2019). A summary of the production results is shown in Table 4.19 below.

Table 4.19: Case Study #4 Production Results

Case Study #4		
Part	Rocket Engine Injector Head	
Company	ArianeGroup	
	Traditional Manufacturing	Additive Manufacturing
Material	Nickel Inconel 718	EOS Nickel-based Alloy (IN718)
Production Time	3 months (480 hours)	65 hours
Number of Parts	248	1
Assembly Weight	*1000*	*700*

Table 4.19 above, shows the component differences from traditional and additive manufacturing. The traditional manufacturing produced component includes different processing steps, such as casting, brazing, welding, and drilling (Electro Optical Systems, 2019). The total production time for the traditional manufacturing assembly was three months (Electro Optical Systems, 2019). The total production time for the additive manufacturing part was 65 hours (Electro Optical Systems, 2019). A visual of the rocket engine injector head is shown in Figure 4.4 on page 48.

Figure 4.4: Rocket Engine Injector Head (Electro Optical Systems, 2019).

Figure 4.4 above, shows the additive manufacturing produced rocket engine injector head. The additive manufacturing process was able to simplify the 248-part assembly to a single component (Electro Optical Systems, 2019). Due to product confidentiality, the weight was not given, but the other case studies experience 30%-40% reduction in weight for additive manufacturing. An assumption will be used for the part weight at 1000 grams for the traditional manufactured part. The additive manufactured part will be 30% less at 700 grams.

The material used on the additive manufacturing component is the proprietary EOS nickel-based alloy IN718 (Electro Optical Systems, 2019). Electro Optical Systems nickel alloy IN718 has excellent mechanical properties at temperatures up to 700°C making it ideal for high temperature applications (Electro Optical Systems, 2021b). The material used in the traditional manufacturing part was not available, so an assumption is made. Nickel Inconel 718 is a commonly used material for the aerospace industry (Standridge, 2014).

The cost of material was determined based on estimates from material suppliers and similar machines. Nickel Inconel 718 bar stock one-inch diameter varies in price from $316.97 up to $1775.03 depending on the length (OnlineMetals.com, 2021). Nickel Inconel 718 bar stock two-inch diameter varies in price from $574.66 up to $3124.37 depending on the length (OnlineMetals.com, 2021). A summary of the average price for Nickel Inconel 718 is shown in Table 4.20 below.

Table 4.20: Nickel Inconel 718 Average Bar Price

Nickel Bar-2"								
$/bar	574.66	1071.26	1506.41	1785.36	2120.12	2477.18	2811.94	3124.37
Length (Inch)	12.00	24.00	36.00	48.00	60.00	72.00	84.00	96.00
Length (CM)	30.48	60.96	91.44	121.92	152.40	182.88	213.36	243.84
Diameter (Inch)	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Diameter (CM)	5.08	5.08	5.08	5.08	5.08	5.08	5.08	5.08
Volume (cm^3)	617.78	1235.56	1853.33	2471.11	3088.89	3706.67	4324.44	4942.22
Density (g/cm^3)	8.19	8.19	8.19	8.19	8.19	8.19	8.19	8.19
Material Weight (g/bar)	5059.60	10119.20	15178.80	20238.40	25298.00	30357.60	35417.20	40476.80
Material Price ($/g)	0.11	0.11	0.10	0.09	0.08	0.08	0.08	0.08
Nickel Bar-1"								
$/bar	316.97	608.59	855.82	1014.30	1204.48	1407.34	1597.52	1775.03
Length (Inch)	12.00	24.00	36.00	48.00	60.00	72.00	84.00	96.00
Length (CM)	30.48	60.96	91.44	121.92	152.40	182.88	213.36	243.84
Diameter (Inch)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Diameter (CM)	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54
Volume (cm^3)	154.44	308.89	463.33	617.78	772.22	926.67	1081.11	1235.56
Density (g/cm^3)	8.19	8.19	8.19	8.19	8.19	8.19	8.19	8.19
Material Weight (g/bar)	1264.90	2529.80	3794.70	5059.60	6324.50	7589.40	8854.30	10119.20
Material Price ($/g)	0.25	0.24	0.23	0.20	0.19	0.19	0.18	0.18
Average Price ($/g)	***0.149***							

Table 4.20 above, shows the average price for nickel Inconel 718 is $0.149 per gram. The average price was calculated from the price per bar divided by the weight of the bar. The material weight was calculated by multiplying the volume of a bar and the material's density property. Since the cost of EOS material is not readily available, another assumption is made. Similar metal printing powders from Markforged range from $0.65 to $1.65 per gram (Markforged, 2021a). The assumption for the EOS nickel-based alloy IN718 cost is $1.65 per

gram. The calculation for the cost of traditional manufacturing part is shown in Table 4.21 below.

Table 4.21: Case Study #4 Traditional Manufacturing Part Cost

C_Traditional Manufacturing	**Case Study #4**
Material Cost per g	0.149
Part Weight (g)	1000
Material Cost, Part (MI_Trad)	148.61
Production Cost per hour	80
Productuon time (hours)	480
Production Cost (P_Trad)	38400.00
Part Cost (C_Trad)	38548.61

Table 4.21 above, shows the estimated cost of traditional manufacturing for the injector head component is $38548.61 per part. The part cost is a total of $148.61 in material and $38400.00 in production cost. The calculation for the cost of additive manufacturing is shown in Table 4.22 below.

Table 4.22: Case Study #4 Additive Manufacturing Part Cost

C_Additive Manufacturing	**Case Study #4**
Material Cost per g	1.65
Part Weight (g)	700
Material Cost (MI_AM)	1155.00
Production Cost per hour	24.04
Productuon time (hours)	65
Production Cost (P_AM)	1562.50
Part Cost (C_AM)	2717.50

Table 4.22 on page 50 shows the estimated cost of additive manufacturing for the control hydraulic component is $2717.50 per part. The part cost is a total of $1155.00 in material and $1562.50 in production cost. The difference in the two manufacturing costs was used to calculate the per part savings to determine the return on investment (ROI). A summary of the ROI calculation is shown in Table 4.23 below.

Table 4.23: Case Study #4 Return on Investment

	Case Study #4
Per Part Savings	35831.11
Cost of Printer: EOS M 400	1500000.00
Parts to Achieve ROI	41.86
Print Time (hours)	65
Production Time (hours/week)	120
Parts Per Week	1.8
Weeks to Achieve ROI	22.68

Table 4.23 above, shows the time to achieve the return on investment (ROI) payback is 22.68 weeks. The per part savings is the difference between the parts costs for traditional and additive manufacturing. The cost of the printer divided by the per part savings equals the total number of parts to achieve the ROI payback. Since the printer can run unmonitored overnight, the production time is 24 hours per day for five working days per week. At 65 hours per part, 1.8 parts can be produced per week. 41.86 parts are required to achieve the ROI, at 1.8 parts per week equals 22.68 week for the payback period.

The next step was to compare the mechanical properties of the additive manufacturing material to the Nickel Inconel 718. The material used on the additive manufacturing component is the EOS nickel-based alloy IN718 (Electro Optical Systems, 2019). A summary of the material properties and composition is shown in Table 4.24 below.

Table 4.24: Case Study #4 Material Properties and Composition

Material #3 Nickel Alloy		
	Traditional Manufacturing	**Additive Manufacturing**
Material Spec	**Nickel Inconel 718**	**EOS Nickel-based Alloy (IN718)**
Density (g/cm^3)	8.19	8.15
Ultimate Tensile Strength (MPa)	1100	1040
Yield Strength (MPa)	980	710
Elongation @ Break (%)	25	26
Material Composition	**Nickel Inconel 718**	**EOS Nickel-based Alloy (IN718)**
Aluminum (Al)	0.20 - 0.80 %	0.20 - 0.80 %
Boron (B)	<= 0.0060 %	<= 0.0060 %
Carbon (C)	<= 0.080 %	<= 0.080 %
Chromium (Cr)	17 - 21 %	17 - 21 %
Cobalt (Co)	<= 1.0 %	<= 1.0 %
Copper (Cu)	<= 0.30 %	<= 0.30 %
Iron (Fe)	17%	Balance
Manganese (Mn)	<= 0.35 %	<= 0.35 %
Molybdenum (Mo)	2.8 - 3.3 %	2.8 - 3.3 %
Nickel (Ni)	50 - 55 %	50 - 55 %
Niobium (Nb) / Columbium (Cb)	4.75 - 5.5 %	4.75 - 5.5 %
Phosphorus (P)	<= 0.015 %	<= 0.015 %
Silicon (Si)	<= 0.35 %	<= 0.35 %
Sulfur (S)	<= 0.015 %	<= 0.015 %
Titanium (Ti)	0.65 - 1.15 %	0.65 - 1.15 %

Table 4.24 above, shows the similarities of the printed EOS nickel-based alloy IN718 and the nickel Inconel 718. Nickel Inconel 718 has a density of 8.19 g/cm3 (MatWeb, 2021b). Electro Optical Systems nickel-based alloy IN718 has a density of 8.15 g/cm3 (Electro Optical Systems, 2016). Inconel alloy 718 has an ultimate tensile strength of 1100 MPa, yield strength of 980 MPa and elongation at break of 25% (MatWeb, 2021b). Nickel alloy Inconel 718 has a material composition of 50% nickel, and 50% a mixture of other metals (Tech Steel and

Materials, 2021). Electro Optical Systems nickel IN718 has an ultimate tensile strength of 1040 MPa, yield strength of 710 MPa and elongation of 26% (Electro Optical Systems, 2016). Electro Optical Systems nickel IN718 has an identical material composition as nickel alloy Inconel 718 (Electro Optical Systems, 2016).

4.7 Results Summary and Impact

Additive manufacturing materials and equipment has evolved over the years to offer increased design freedom, reduced lead times, and less material waste (Bikas et al., 2015). The problem can be measured by the reduction in manufacturing time, as high as 75% in some industries (Ngo et al., 2018). A summary of the production time for the four case studies is shown in Table 4.25 below.

Table 4.25: Production Time Summary

	Traditional Manufacturing Production Time (hours)	Addtive Manufacturing Production Time (hours)
Case Study #1	560	19
Case Study #2	500	80
Case Study #3	32	8
Case Study #4	480	65

Table 4.25 above, emphasizes the reduction in production time with additive manufacturing. Manufacturing cost and time are saved through elimination of rough machining and a reduction in the programming effort (Abdulhameed et al., 2019). One 3D printer can completely build a part with complex geometry, eliminating multiple steps in the process (Abdulhameed et al., 2019). The reduction in production time results in a significant difference

in part costs between traditional and additive manufacturing. A summary of the manufacturing costs and payback for the four case studies is shown in Table 4.26 below.

Table 4.26: Manufacturing Cost and Payback Summary

	Traditional Manufactuing Part Cost (dollars)	Addtive Manufactuing Part Cost (dollars)	Return on Investment Payback (weeks)
Case Study #1	44,812.23	615.23	5.37
Case Study #2	40,043.30	2,393.08	26.56
Case Study #3	2,630.42	939.81	59.15
Case Study #4	38,548.61	2,717.50	22.68

Table 4.26 above, shows the reduced part cost using additive manufacturing. Thus, the results supported a rejection of the null hypothesis in favor of the alternative hypothesis. There was a significant difference in the production costs for traditional and additive manufacturing.

The results show a significant difference in manufacturing time and cost. However, as the results show there is a similarity in material properties. The results compared three types of materials; aluminum, titanium alloy, and nickel alloy. The materials used in additive manufacturing have similar ultimate tensile strength, yield strength, and elongation as the materials used in traditional manufacturing. The material comparisons also show a similar density and material composition. The remaining conclusions and recommendations in Chapter Five present areas for continuing research.

CHAPTER 5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary

Additive manufacturing is the process of joining material layer by layer, using data from a 3D model, to create a part (Bikas et al., 2015). Additive manufacturing allows for rapid production of customized objects by simply uploading a new 3D CAD file in the software (Gilchrist, 2016). The benefits of additive manufacturing can be measured by the reduction in manufacturing time, as high as 75% in some industries (Ngo et al., 2018). The research showed that the investment yields a payback between as low as five weeks.

The research results presented in Chapter Four illustrate the difference between traditional and additive manufacturing time and cost. The four case study results use the same 3D printer, the Electro Optical Systems EOS M 400 direct laser sintering machine (Electro Optical Systems, 2020b). The first case study is the A350 XWB cable mounting bracket manufactured by Sogeti High Tech (Electro Optical Systems, 2018a). Production time was reduced from 560 hours down to 19 hours. The number of parts was reduced from 30 to one single component. The estimated cost savings equals $44,197 per cable mounting bracket. The second case study is the Sentinel satellite antenna bracket manufactured by RUAG Holding (Electro Optical Systems, 2018b). Production time was reduced from 500 hours down to 80 hours. The estimated cost savings equals $37,650 per satellite antenna bracket. The third case study is the primary flight control hydraulic component manufactured by Liebherr-Aerospace (Electro Optical Systems, 2018c). Production time was reduced by 75%. The estimated cost savings equals $1,690 per hydraulic component. The fourth case study is the rocket engine injector head manufactured by ArianeGroup (Electro Optical Systems, 2019). Production time was reduced from 480 hours down to 65 hours. The number of parts was reduced from 248 to one single component. The estimated cost savings equals $35,831 per rocket engine injector head.

5.2 Conclusions

The research sought to increase process flexibility by implementing additive manufacturing in production. The results did align with current available research as the use of additive manufacturing increased flexibility and reduced costs. The cost reductions from utilizing additive manufacturing are the result of the reduction in both production time and reduction in material waste. The results provide a start, but there were some limitations to the research. The research was limited to one printer, using metal materials, all in the aerospace industry. Further areas of research in the use of additive manufacturing are identified to complement the findings of the current research paper

5.2.1 Research Alignment with Review of Literature

The research results show the use of additive manufacturing can save production time and material waste. Additive manufacturing materials and equipment has evolved over the years to offer increased design freedom, reduced lead times, and less material waste (Bikas et al., 2015). Companies in the aerospace industry are including additive manufacturing in the production process to reduce manufacturing time as high as 75% (Ngo et al., 2018). The four case studies presented in the results show a significant reduction in production time. There were additional savings in material usage and material waste in addition to production time savings. New technologies, such as additive manufacturing, can overcome the limitations of traditional machines and reduce the number of required parts (Ngo et al., 2018). Three-dimensional printing builds up in layers to minimize material usage to produce only the required geometry (Kearney, 2017).

One of the challenges of additive manufacturing is producing parts with the same strength and quality as traditional manufacturing methods. The research results show the additive manufacturing produced parts have adequate strength properties compared to the parts produced with traditional manufacturing. The research examples used the same 3D printer, the Electro Optical Systems EOS M 400 direct laser sintering machine for industrial production (Electro Optical Systems, 2020b). Metal selective laser sintering (SLS) has a high degree of accuracy and quality making it one of the most used printing processes (Bikas et al., 2015).

5.2.2 Limitations of Research

While the findings demonstrated the significant financial savings from production time and material waste reduction, there are limitations to the research. The research was limited to four best-case scenarios from the same manufacturing industry. All four examples produced components used in aerospace assemblies. The research was also restricted to metal alloy materials on the same 3D printer. All four examples used the Electro Optical Systems EOS M 400 direct laser sintering machine with aluminum, titanium, and nickel materials. Other types of additive manufacturing or materials may not have the same financial benefits. The research limitations provide opportunities for future research.

5.2.3 Interpretation of Findings

The benefits of utilizing additive manufacturing can be seen in the reduction of production time and material waste. The first case study reduced production time from 560 hours down to 19 hours. The second case study reduced production time from 500 hours down to 80 hours. The third case study reduced production time by 75%. The fourth case study reduced production time from 480 hours down to 65 hours. The elimination of multiple machines and multiple operators from traditional manufacturing resulted in the reduced production time. The hourly production cost was lower for additive manufacturing in addition to the reduced production time. The average U.S. machine shop rate is 60 to 80 dollars per hour (CNC Machinist Training, 2021). The research shows the production cost of additive manufacturing is $24 per hour.

Another positive fining for the research results is the material physical and mechanical properties. The three alloy materials used in the research include aluminum, titanium and nickel based. The material density is similar for both additive manufacturing and traditional manufacturing resulting in a similar raw material weight. The optimized part design allows for less material used and a lower part cost in additive manufacturing. The alloy materials used in additive manufacturing have similar strength to the materials used in traditional manufacturing. Additional research, including functional testing, can ensure that the 3D printed components can withstand the loads in typical conditions.

5.3 Recommendations for Future Work

The research provided positive results, but there are areas that need further research to complement the findings of the current research paper. Those areas are:

1. Research the real cost of the materials used on the Electro Optical Systems (EOS) M 400 3D printer.

2. Research the cost of shipping for both the traditional and additive manufacturing components.

3. Research the manufacturing location for each case study and the effect on the manufacturing costs.

4. Conduct functional testing of additive manufactured components to ensure usability.

5. Research additional components or assemblies that can take advantage of the use of additive manufacturing.

6. Research the functionality of additional material types, such as polymers, that are used in other additive manufacturing technologies. Polymers are the most common materials used in the 3D printing industry (Ngo et al., 2018).

The research results presented for the project prove that additive manufacturing can provide economic benefits, such as reducing the costs of manufacturing. Additive manufacturing materials and equipment has evolved over the years to offer increased design freedom, reduced lead times, and less material waste (Bikas et al., 2015). Expanding on the research into additional materials, such as plastics and ceramics, would increase the use of additive manufacturing in production.

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APPENDIX A. THREE MINUTE PITCH