University of
Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/Specialization: Industrial Economics Project Management	Spring semester, 2016 Open access
Writer: Steffen Solberg	………………………………………………………… (Writer's signature)

Faculty supervisor:

Roy Endre Dahl

Thesis title:

Cost-Efficient Low-Volume Production Through Additive Manufacturing

Credits (ECTS): 30

Key words: 3D Printing, Additive Manufacturing, Selective Laser Sintering / Melting, Fused Filament Fabrication, Subtractive Manufacturing, Aluminium, Plastic, ABS, Nylon	**Pages: 65** + enclosure: 7 Stavanger, 15th of June, 2016

Master Thesis

Department of Industrial Economics, Risk Management and Planning

Cost-Efficient Low-Volume Production Through Additive Manufacturing

Universitetet
i Stavanger

Steffen Solberg

University of Stavanger

June 15, 2016

Abstract

Additive manufacturing, commonly known as 3D Printing, is a production method of rising popularity. The method works by adding layers of material, in contrast to subtracting, which is the dominating method today. The objective of this thesis has been to evaluate the cost-efficiency of producing relatively complex parts through additive manufacturing, compared to subtractive methods with production volumes less than 20 units.

Initial findings narrow the additive methods down from seven, to two methods (Selective Laser Sintering/Melting and Fused Filament Fabrication) which are found best fit for end use parts. Data is gathered by acquiring price quotes from manufacturing companies for two plastic and two aluminium parts, through subtractive and additive methods. In order to look for intersections found at intermediate production volumes, the companies were asked to give price for 1, 5 and 20 units of the same item.

Compared to subtractive methods, additive manufacturing processes are found to exhibit less cost-decrease per additional unit produced. The cost of producing a 150gram plastic part through the additive process was found to be between a quarter, and half the cost of the subtractive machining processes. In comparison, for a 15 gram part, additive manufacturing was found to be even more cost-efficient, with prices ranging between 10% and 20% of the alternative.

The metal additive manufacturing process was found to be 15% cheaper than the subtractive at producing one single small part (100gram), whereas in contrast, it was 50% more expensive when producing 20 units. For manufacturing larger parts (500gram), it was found to be between 75 and 150% more expensive than the subtractive machining.

As such this thesis complements existing literature on when to choose an additive process over the subtractive, and shows that whilst plastic additive processes are very cost-efficient for low volumes, metal additive manufacturing still has a way to go before becoming the natural choice for low-volume production.

Preface & Acknowledgements

This work is made in partial fulfillment of a Masters degree in Industrial Economics at the University of Stavanger, and concludes my six years of engineering studies through which i have gained vast amounts of knowledge that I will try to use to its full potential. This study has proven to be a great way to learn about new subjects and gain a thorough understanding of the mechanisms involved in production.

I'd like to extend my gratitude to the companies and individuals that have helped me gain deep insight into matters of high complexity, your help has been truly invaluable.

To my supervisor, Roy Endre Dahl, who has provided me with great input towards looking at methods from another perspective, and given me the needed guidance towards structuring this thesis.

To Anders Reve at Simplify AS for helping me narrow down the vast amount of information available on additive manufacturing methods.

To Geir Egil Rosland at Aarbakke AS, whose knowledge of the CNC machining processes are undeniable. Your cooperation has been of fantastic use when estimating the time use and pricing of machining processes.

To Eivin Strømland at Promet AS, for helping me understand the differences in processes, and giving great inputs to the balancing act between subtractive and additive manufacturing methods.

To Jonas Mersch at SLM Solutions, and Pär Jansson at Electro Optical Systems Nordic AB who provided me with their knowledge of the processes that are going on behind the scene of machine manufacturers.

To all my classmates at INDØKS, UiS Subsea and ION Racing. Your work makes this university a much brighter place.

And finally to my family, and fantastic girlfriend, Beate Stange, who supports me in my endeavors, no matter what they might be. You streamline my life and for that I am ever grateful.

Table of Contents

1 Introduction **1**

2 Theory **3**

2.1 Low and High-Volume Production . . . 3
2.2 Subtractive Manufacturing and CNC Machining . . . 4
  2.2.1 Tri/Four/Five-Axial CNC milling . . . 4
  2.2.2 Multi-tasking machines . . . 5
2.3 Additive Manufacturing . . . 5
2.4 Economics of Additive Manufacturing . . . 7
2.5 Additive manufacturing methods . . . 7
  2.5.1 Limitations of Additive manufacturing methods . . . 8
  2.5.2 Fused Filament Fabrication . . . 9
  2.5.3 Vat Photopolymerization: Stereolithography (SLA) . . . 11
  2.5.4 Material Jetting (Multijet Modeling) . . . 11
  2.5.5 Binder Jetting . . . 13
  2.5.6 Directed Energy Deposition . . . 13
  2.5.7 Powder Bed Fusion - Selective Laser Sintering/Melting & Electron Beam Melting . . . 14
  2.5.8 Sheet Lamination (Ultrasonic Consolidation) . . . 16
2.6 Cost structure of production . . . 17
  2.6.1 Cost Structure Associated with CNC Milling . . . 17
  2.6.2 Cost Structure Associated with Additive Manufacturing . . . 18
2.7 Previous Work on Price-Efficiency of Additive Manufacturing . . . 19

3 Methodology **21**

3.1 Interview Guide . . . 21
3.2 Evaluation criteria for manufactured parts . . . 21
  3.2.1 Complexity . . . 22
  3.2.2 Quality . . . 22
  3.2.3 Cost . . . 24
  3.2.4 Repeatability . . . 24
3.3 Quote retrieval . . . 25

4 Results and Discussion **27**

4.1 Additive methods evaluated . . . 27
4.2 Evaluated Parts . . . 28
  4.2.1 Part I: Plastic Thruster Housing . . . 28
  4.2.2 Part II: Plastic Propeller . . . 29

    4.2.3 Part III: Metal Race Car Front Upright 31
    4.2.4 Part IV: Metal Race Car Rear Suspension Bracket 32
  4.3 Cost Comparison of AM and SM methods 33
    4.3.1 Part I: Plastic thruster housing 33
    4.3.2 Part II: Plastic Propeller 36
    4.3.3 Part III: Metal Race Car Front Upright 36
    4.3.4 Part IV: Metal Race Car Rear Suspension Bracket 38
  4.4 Drivers for Implementing Additive Manufacturing 40
    4.4.1 Competence Requirements 40
    4.4.2 JIT - Just In Time 40
    4.4.3 High Variation & Mass Customization 41
    4.4.4 Possible Disruptive Effects on Existing Machining Markets . . 42
    4.4.5 Geometrical Freedom & Bio-mimicking 43
    4.4.6 Assembly Simplification 44
    4.4.7 Material Utilization & Energy Savings 44
    4.4.8 Reduced use of Hazardous Cutting Fluids 44
    4.4.9 Supply Chain Alteration 45
  4.5 Challenges Associated With Adoption of AM 46
    4.5.1 Limitations of Traditional CAD Software 46
    4.5.2 Cost of AM Systems Contribution to Parts Price 47
    4.5.3 Cost of Materials / Lack of Material Standards 48

5 Conclusion **50**
  5.1 Price performance of Additive Manufacturing of Plastic Parts 50
  5.2 Price Performance of Additive Manufacturing of Aluminium Parts . . 51
  5.3 Preferential steps towards increased adoption of AM 51

6 Further work **52**

Acronyms

ABS acrylonitrile butadiene styrene. 10, 29
AM Additive Manufacturing. 1, 3, 5, 6, 9, 11, 13, 15, 18–24, 26, 27, 31, 34, 36, 40–42, 45, 46, 51

CAD Computer-aided design. 18, 46, 51
CAM Computer-aided manufacturing. 46, 47, 51

DED Directed energy deposition. 6, 13, 27
DFM Design For Manufacturing. 22

EBM electron beam melting. 6, 8, 15, 52

FDM™ fused deposition modeling. 6, 15, 19, 20, 25, 28, 29, 34, 47, 49, 50
FFF fused filament fabrication. viii, 6, 9–11, 13, 15, 18, 23, 25, 28, 34, 36, 50

JIT Just In Time. 40, 41

MRR Material Removal Rate. 5, 29

PBF Powder Bed Fusion. 8, 13, 34, 36, 49, 50
PET polyethylene terephthalate. 11
PLA polylactic acid. 10
POM Polyoxymethylene. 29

RFQ Request For Quote. 25
RP Rapid Prototyping. 1

SLA stereolithography. 1, 6, 11, 13, 19, 20
SLM selective laser melting. 6, 8, 15, 28
SLS selective laser sintering. viii, 6, 8, 15, 19, 20, 23, 28, 47, 50
SSS Solid State Sintering. 15
STL standard tesselation language. 18

WYSIWYB What you see is what you build. 5

Glossary

Buy-to-fly Ratio Is a definition found in the aerospace industry, which describes the ratio of material volume/weight of the original stock, prior to machining, divided by the material volume/weight of the completed part. As such it is a measure of material efficiency. E.g. a part beginning as a 2kg piece of aluminium, but after processing it weighs 1kg, this is a 2:1 Buy-to-fly Ratio. 5, 36, 38, 44

CNC is short for computer numerical control. These are subtractive manufacturing machines which are controllable through a computer.. 1, 3, 4, 9, 13, 17–19, 22–24, 26, 27, 32, 34, 36, 38, 40, 45, 47, 50, 51

nylon are a group of thermoplastic polymers, which was first used as a material for womens stockings. However in additive manufacturing and engineering it is a structurally strong plastic with relatively low coefficient of friction. Nylons are often also called Polyaramides(PA). 11

slicer is a piece of computer software creating multiple two-dimensional layers from a three dimensional CAD-model, in order to create machine instructions for additive manufacturing systems. 18, 47

stereolithography is an additive manufacturing process utilizing photopolymerization in order to harden or cure a resin into a polymer. 6, 27

List of Figures

1 Axes of operation for 3/4/5-axis cnc machines[1][2][3] 4
2 Traditionally machined parts made out of aluminium 6082-T6 in a Mazak 430A Vertical Mill at the University of Stavanger 6
3 Overview of a FFF machine[4] 9
4 Varying infill percentage[5] 10
5 VAT Photopolymerization through a stereolithography machine[6] . 12
6 Overview of a Additive manufacturing cell utilizing the material jetting method[7] 12
7 Directed energy deposition method for manufacturing an object[8] . 14
8 The sintering process[9] 15
9 The process of creating parts through powder bed fusion[10] 16

10 Cardboard sheet lamination and the ultrasonic welding method[11] [12] 17

11 A slicer software is creating two-dimensional layers from a three-dimensional model[13] 19

12 The process of creating parts through additive and subtractive manufacturing processes 20

13 A comparison of the surface quality of a part manufactured with a low cost fused filament fabrication (FFF) machine versus that of a high-end selective laser sintering (SLS) machine[14][15] 23

14 An overview of part I: thruster housing, shown with transparent propeller(Part II) and DC outrunner motor. 29

15 A cross-sectional view of part I: the thruster housing 30

16 A side view of part II: the auv propeller. Note the thin walls at the ends of the NACA airfoil blade, together with the varying blade pitch 31

17 Engineering drawings of part III: The metal race car front upright[16] 32

18 Engineering drawings of part IV: The metal race car rear suspension bracket[17] 33

19 Cost of having part I produced at multiple volumes through SM and AM 35

20 Cost of having part II produced at multiple volumes 37

21 Cost of having part III produced at multiple volumes 38

22 Cost of having part IV produced at multiple volumes 39

23 Process overview for additive manufacturing of hearing aids at Siemens Hearing Instruments Inc. 42

24 Topology optimized skeleton frame motorcycle, by airbus APWORKS[18] 43

25 Average costs of CNC vs AM for the aluminium parts 51

1 Introduction

Manufacturing of parts can be done in a multitude of ways in order to achieve certain characteristics, such as strength, finish, and density on the final product. The most efficient method for producing a specific item varies significantly with changing volume and geometric complexity. The final product will also exhibit traits which are inherent for the chosen production method. One of the newest methods of manufacturing items is Additive Manufacturing (AM). AM was originally used as a concept under the name Rapid Prototyping (RP) in Charles Hull's patent US4575330-A[19] published 11th of march 1986, which described the first method of manufacturing items through an additive process rather than subtractive. The process was named stereolithography (SLA), and since then multiple new methods have helped AM to continuously evolve into a manufacturing method which shows signs of being a disruptive technology, altering the way products are made. Like other emerging technologies before it, it is common for us to overestimate the potential in short-term, and underestimate the long term effects. Therefore a potential lies in evaluating the status of the technology today, while still considering the long term effects.

Previous theses on the theme of AM have for the most part been focused on quality aspects of the parts produced. Thorough investigations on the microstructure and surface roughness together with general strength and quality of the parts manufactured through AM have been done so that we can make sure that they have documented material properties. As a student in industrial economics we are encouraged to look past the engineering focus which are on the technical features, and look at the systems with a broad overview. As such the focus has been on the cost aspect of using this new technology in ways which improve competitiveness in demanding markets, such as the low volume market.

AM is considered to have a quite flat cost curve compared to the traditional manufacturing methods, especially those which utilize moulds, and could therefore favour very low production volumes. Previously low-volume manufacturing have often been done through a machining company specializing in low-volume or prototype production through CNC machining. As CNC machining works by subtracting material through a computer controlled cutting process, it requires significant start-up costs in terms of programming and setup, thereby exhibiting a high initial price which is reduced throughout the units produced.

The goal is then to look at how new innovative products can be brought to life without regard to production numbers, as many of today's products require significant volume or very high prices in order to become profitable. The comparison of the relatively flat cost curve achieved with additive manufacturing towards the initially high cost of machining, can provide valuable insight towards finding the crossover points at which one or the other is more cost-efficient.

As such the thesis question is narrowed down to;

- **Can additive manufacturing methods be used as a cost efficient alternative to CNC Machining, when production volumes are less than 20 units?**

in order to fulfill this research question I must

- explain the additive manufacturing methods
- verify which methods create parts that are fit for use over time
- establish how additive manufacturing impacts other aspects of the manufacturing chain

In the thesis four sample parts are used as basis of comparison between subtractive and additive manufacturing methods. The cost of having these parts made by a third-party is used as the main evaluation criteria. The four parts are split into two plastic and two metal parts, where they exhibit increasing geometrical complexity, in order to see how this intricacy affects costs. This is done for both the metal and plastic parts, as there are significant differences in the maturity of these methods.

As such the thesis compares the traditional versus the new, the established versus the untried; the David and Goliath of manufacturing methods.

2 Theory

This section of the thesis will aim to enlighten the reader about the methods and challenges associated with manufacturing plastic and metal items. It will also introduce the AM methods which will be evaluated for final parts use, together with a view on how low volume production differs from the classic high volume manufacturing methods typically employed in series production.

2.1 Low and High-Volume Production

High-volume production is the basis for mass production, and almost every product that we encounter in our day-to-day life is produced through what can be considered high-volume production methods, pioneered by Henry Ford in 1908.

The method thrives by achieving cost-savings through efficient spread of fixed costs throughout its volumes, and to some degree by allowing the company to purchase products and materials in bulk. Highly specialized costly equipment and tooling allow for unprecedented efficiency at producing low-variation, high volume parts, often through methods such as injection molding, stamping or sand casting. The production plants often utilize statistical process control for achieving very low inter-part variation, and low defect rates as a result.

The capital costs associated with production tooling and associated machinery cannot be efficiently spread in a low-volume environment, and lead to the methods often becoming prohibitively expensive. Therefore production is often done through manual labor from experienced craftsmen or outsourced to a company specializing in low volume utilization of CNC machining. Novel approaches together with our designers' skills and experience can help towards minimizing costs, but they will never reach the low cost levels of automated mass production, and as such many projects are canceled due to the high costs associated with producing the project deliverables. Low production volumes are often found in products which follow a high pricing strategy, such as oilfield tooling, aerospace components and exotic vehicles.

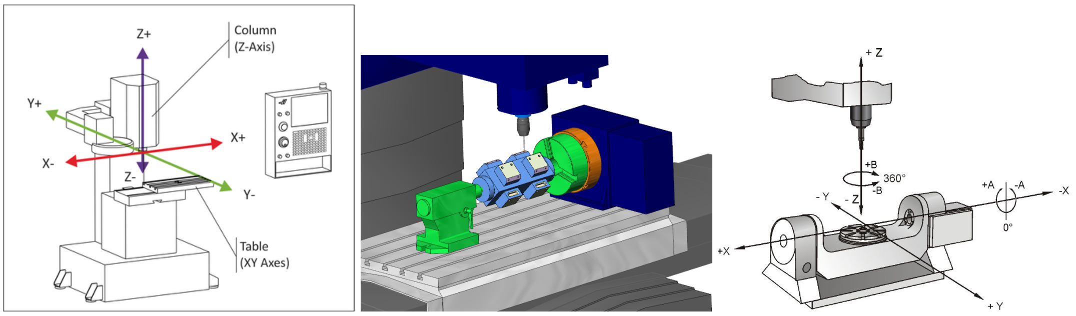


Figure 1: Axes of operation for 3/4/5-axis cnc machines[1][2][3]

2.2 Subtractive Manufacturing and CNC Machining

Subtractive manufacturing, of which CNC machining is a sub-genre, generally bases its methods upon the removal of material from a solid block of homogeneous material often referred to as "stock" or "billet". Cutters gradually remove material from that stock in order to create tooling for injection moulding, dies, castings and parts which are put directly to use. This requires an operator to pre-program the cutting operations individually on a CNC machine, or manually control the operations. Schischke et al. [20] states that of the 3.5 million machine tools available in Europe today, 750.000 of those are CNC controlled. This shows that the adoption of automation tools throughout Europe has happened at a slower rate than anticipated when the systems were released, and that large amounts of manual labor is still in use today.

2.2.1 Tri/Four/Five-Axial CNC milling

Figure 1 shows the degrees of freedom for three, four and five axis milling machines. In a tri-axial milling machine the cutter can be moved in the three primary axes, and in this case I will use a vertical machining center as an example, which means that you control the X(Right-Left), Y(Forwards-Backwards) and Z(Up-Down) axes. As such only contours which are accessible from directly above are able to be milled away. Figure 2 shows parts which have been machined in a three-axis vertical machining center, and shows how all features are cut vertically without changing the angle of the cutting tools. Notice the matte look achieved through bead blasting on the bottle opener to the right, which shows how differences in surface roughness affects the look of products.

Figure 1 further shows how the fourth and fifth axis is implemented through rotation of the workpiece, which introduces the ability to create more complex parts, by improving accessability to the sides of the part.

2.2.2 Multi-tasking machines

Since the late-nineties and early two-thousands we have also seen the introduction of combinational milling/turning machines with up to eleven axes. These machines reduce manual handling and fixturing operations of stock, by increasing capital investment in machinery, and by using round bar as its basis for creation of parts. There are almost no limits to the complexity of parts which can be created, but complexity significantly increases the time it takes to complete each part, and internal geometries aren't createable.

As the mentioned methods are based upon the removal of material, it can often be seen to have a poor material usage efficiency, in many cases as low as 10-15%. This is called a high Buy-to-fly Ratio (between 6.6:1 and 10:1) in the aerospace industry and will be used as a measure of material effiency throughout the thesis.

The speed of removal or Material Removal Rate (MRR) is a result of the cutting tool diameter, the tools rotational speed, together with depth and width of cut, with the upper limit being placed on the machine's rated maximum power output, or the cutters ability to not break from the loads it is exposed to. This leads to smaller details taking long time to complete, as the tools become increasingly fragile.

2.3 Additive Manufacturing

According to ASTM additive manufacturing is defined as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies." [21] It is a more or less fully automated process from start to finish, and barely require any manual input throughout its process.

With AM the 3D models geometry is being reproduced by the AM Machine without the designer having to account for the exact production method, and therefore we can say that an AM Machine is a What you see is what you build (WYSIWYB) process. [22] The method is often referred to as "Rapid Prototyping" or "3d-printing", however the term Additive manufacturing is proposed by many as a better term to

Figure 2: Traditionally machined parts made out of aluminium 6082-T6 in a Mazak 430A Vertical Mill at the University of Stavanger

fully incorporate all of the methods found under the umbrella terminology.

The term Additive Manufacturing comprises of at least seven different methods of creating objects. These methods are:

- Material extrusion (fused deposition modeling (FDM™) / FFF)
- Vat photopolymerization: stereolithography (SLA)
- Material jetting
- Directed energy deposition (DED)
- Powder bed fusion (selective laser sintering (SLS)/selective laser melting (SLM) & electron beam melting (EBM))
- Binder jetting
- Sheet lamination (ultrasonic consolidation)

These AM methods are currently at very different levels of maturity, with FDM™ leading the way as the most established method, and sheet lamination being the least examined method. All of these methods were originally conceived as prototyping tools, which means that their focus has been on achieving low cost parts, with minimal functional requirements. As the methods have shown to provide engineers with increased design freedom, companies have begun trying to use these methods for final production parts as well, even with the limitations that they currently exhibit.

2.4 Economics of Additive Manufacturing

The additive manufacturing economy is still considered very small when compared to methods such as injection moulding, milling, stamping and pressing, laser and water cutting together with cutting on a lathe. According to wohlers associates'[23] "wohlers report for 2016" the Additive manufacturing business crossed 5.1 billion USD, compared to GE's estimate of the global manufacturing industry which is 10.5 trillion USD [24]. The wohler report further shows that over 278 000 "desktop printers" were sold in 2015. However in 2014 the manufacturing institute together with PriceWaterhouseCooper did a questionaire with american manufacturing businesses, where 33% of them said that they had not yet implemented any form of additive manufacturing, even for prototypes. Twenty-five percent said that they only use 3d printing for prototypes. Thirteen percent of the companies asked utilized 3d-printing for both prototypes and production, however around three percent of these were done so because their products are impossible to manufacture through traditional methods.[25]

Very complex parts such as jet turbine blades and fuel nozzles are currently being produced by GE aviation in conjunction with Snecma for the LEAP engine. This new turbine engine for large aeroplanes promises fuel savings of up to fifteen percent[26], however with such claims the outright cost of the parts become less important compared to the long term effects of fuel saving. It is however a very important step towards showing that the technology is at a level of maturity which is good enough for use in critical assemblies.

2.5 Additive manufacturing methods

While many hail this new technology for its simplicity and ease of use, it is definitely not without fault, as the characteristic features of these systems are still far behind traditional methods when considering surface roughness and dimensional accuracy. This is expected to continue to improve as the techniques gets traction in industrial markets and the manufacturers get enough data to effectively utilize continuous improvement.

High end additive manufacturing systems, that are inching towards improved accuracy, are still very few and far apart. This could lead people to utilizing cheaper systems for the production of their first additive parts, and could lead to the disappointment of customers. As such the industry has a challenge with regards to machinery, and how it can effectively communicate the differences in end quality when comparing additive systems.

Currently there are only four additive manufacturing systems in Norway which can utilize metals for production of end use parts, of which there are only two that are in the hands of commercial businesses. The machines are placed at the following locations and utilize the following technology;

- NTNU Gjøvik - Arcam A2X - EBM
- SINTEF Trondheim - Concept Laser M2 - SLS
- Promet - SLM Solutions 280HL - SLM
- Tronrud engineering - EOSint M280 - SLS

Commonalities between them are that all of them are Powder Bed Fusion (PBF) type machines, and that their machines are not being utilized anywhere near their potential and stands idle most of the time, due to a very small national market for the services that they provide.

2.5.1 Limitations of Additive manufacturing methods

The additive manufacturing methods still exhibit limitations that might be inhibiting them from being used in a production environment. Most of these limitations are similar for most of the additive systems, and are generally a result of design choices made by the manufacturers of the machines.

When comparing the output from an additive process to that of a subtractive they are very easily separated as the additively produced products have a very distinctive look to them, which comes from the high average surface roughness. This doesn't necessarily lead to products which are inferior, however they look different than what is expected from something produced out of e.g. aluminium. A high roughness value is also normally considered to be detrimental towards the longevity of moving parts for tribological reasons[27], effectively making 3d printed parts incompatible with the use of bearings and sliding surfaces without finish machining. Finish machining in this case means CNC machining certain surfaces

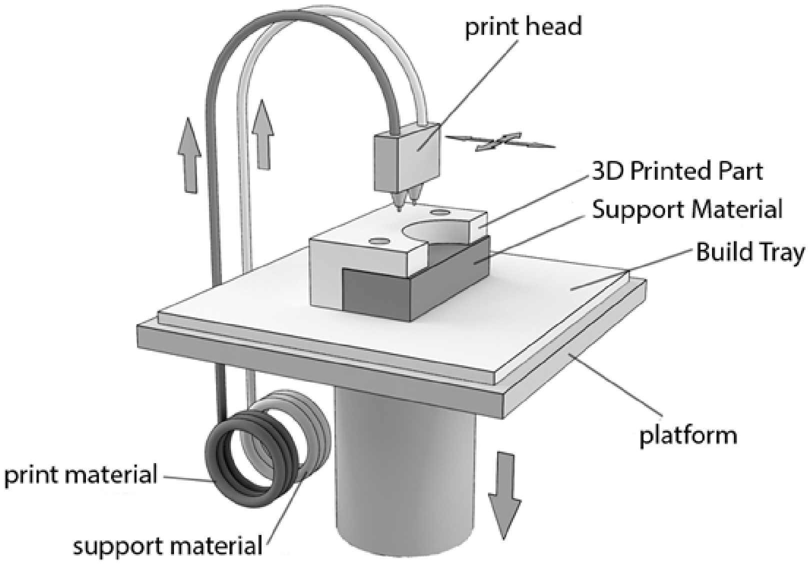


Figure 3: Overview of a FFF machine[4]

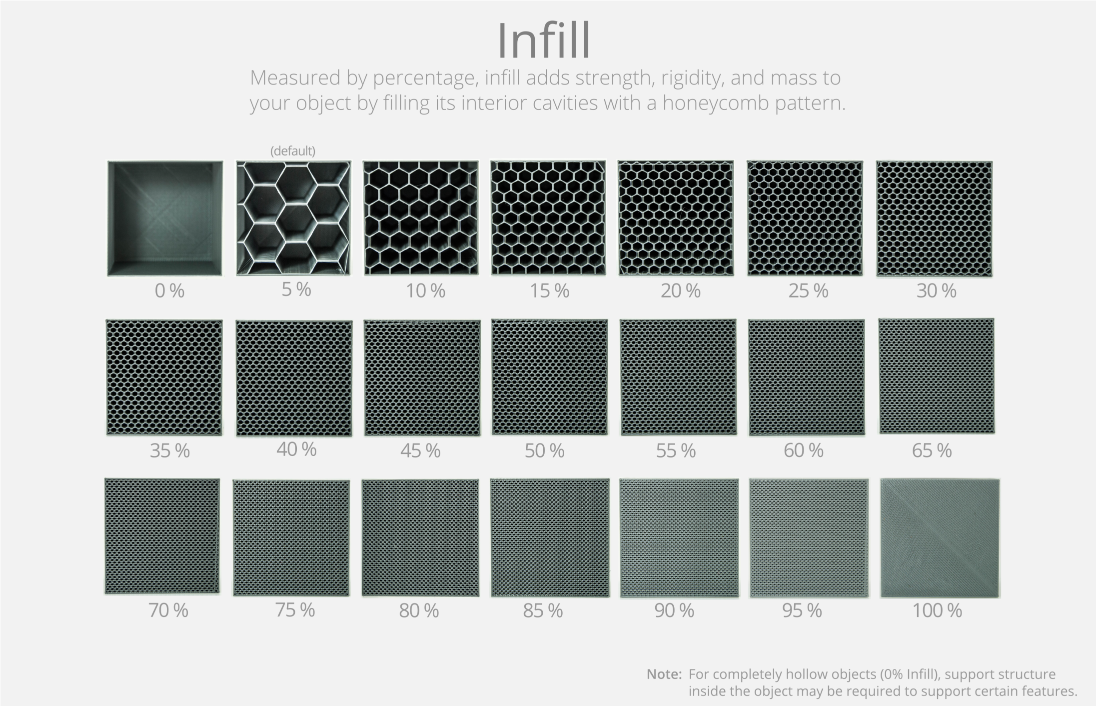
in order to decrease their roughness, as high roughness significantly affects load bearing ability, and increases wear.

AM can still only produce items of relatively small size, as the size of build volumes are generally no larger than $250x250x250mm$. EOS Gmbh's eosint M400 has a build volume of a 400mm cube, whereas a build volume of 800x400x500mm is found in what is currently the worlds largest powder bed fusion AM system (Concept Laser X Line 2000R).[28] This can currently be seen as somewhat restricting when CNC machines of much lower cost work with objects that are much larger.

Due to the low production speed of the processes, they are generally not suited for use in medium to high-volume static processes, which are much better handled through more traditional methods.

2.5.2 Fused Filament Fabrication

FFF is the process of melting a thermoplastic through a print nozzle. The thermoplastic is being introduced to the print nozzle from a coil of material, where the print nozzle deposits material by heating the filament past the glass-transitioning temperature T_g, at which point the thermoplastic will begin to flow. It is important to note that like most amorphous polymers the materials does not exhibit a set melting point, but alters viscosity through increased temperature, and as such the


Infill

Measured by percentage, infill adds strength, rigidity, and mass to your object by filling its interior cavities with a honeycomb pattern.

Note: For completely hollow objects (0% Infill), support structure inside the object may be required to support certain features.

Figure 4: Varying infill percentage[5]

temperature is of utmost importance when using this method. The nozzle extrudes material in a two-dimensional fashion, placing sets of extruded profiles of material side by side creating a flat object, before changing its height doing the same again. As the process continues it is possible to see the individual layers from the side of the object, a feature introduced by the two-dimensional style in which the printers work. Further a secondary extrusion nozzle is often added to the machines in order to create support structures, or scaffolding on which the parts are placed and supported by, often in a different material. The parts which build up a FFF machine can be seen in Figure 3.

To decrease the amount of raw material used in order to manufacture solids, it is common to introduce a structure inside the part, which are called infill structures. These vary in percentage of air or inert gas inside the part, and also the form of structure used. Figure 4 shows varying infill percentage in additively manufactured parts, which significantly decreases weight and material usage while sacrificing some strength.

Some of the advantages of FFF compared to the other methods are the vastly varying materials which can be used. As most thermoplastics are viable solutions, it is possible to use acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polyethylene terephthalate (PET), nylon and even highly engineered mixtures of these giving the exact properties needed in a design. Examples of these highly engineered filaments are Ninjatek's Ninjaflex™, which is a flexible thermoplastic polyurethane that exhibits over 1000% elongation before break.

With the expiration of Stratasys' patent on "Fused Deposition Modeling" (FDM™) in 2009, products utilizing this technique has exploded in the consumer market. This continued development has led to a decline in price for simple additive manufacturing systems and better products as the manufacturers continue to improve upon the technology. These low cost 3d printers can be purchased at costs below 2000$USD, and together with the continued development of the electronics prototyping tools "Arduino" and "Raspberry pi" they represent the core of the maker movement of today. It can however still be noted that with FFF style printers you get what you pay for, and that high-end systems exhibit significantly better properties and dimensional stability. [29]

2.5.3 Vat Photopolymerization: Stereolithography (SLA)

SLA is the original and first method of AM that was invented, and significant work has been done in order to produce as high quality parts as possible at this point of time. In a SLA machine, a liquid photopolymer is placed in a container called the vat. The photopolymer is then activated by radiation, either as ultraviolet light or in some cases visible light, which causes them to solidify into a polymer through a chemical reaction. The level of liquid resin in the vat is adjusted continuously as the piston moves the part so that the lasers/projectors cures the layers into a solid part. This produces a high quality surface finish combined with high resolution, in many cases better than what can be achieved with other AM technologies. Figure 5 shows the parts used in a SLA machine.

2.5.4 Material Jetting (Multijet Modeling)

When 3d-printing an object through the process of material jetting, the machine will use a process similar to an inkjet printer. It places small droplets of a photopolymer onto the base/part, after it will move over while flashing the entire build area with UV-light to activate the photoinitiated polymerization of the individual droplets. As such it can seem that the process is similar to that of an SLA machine,

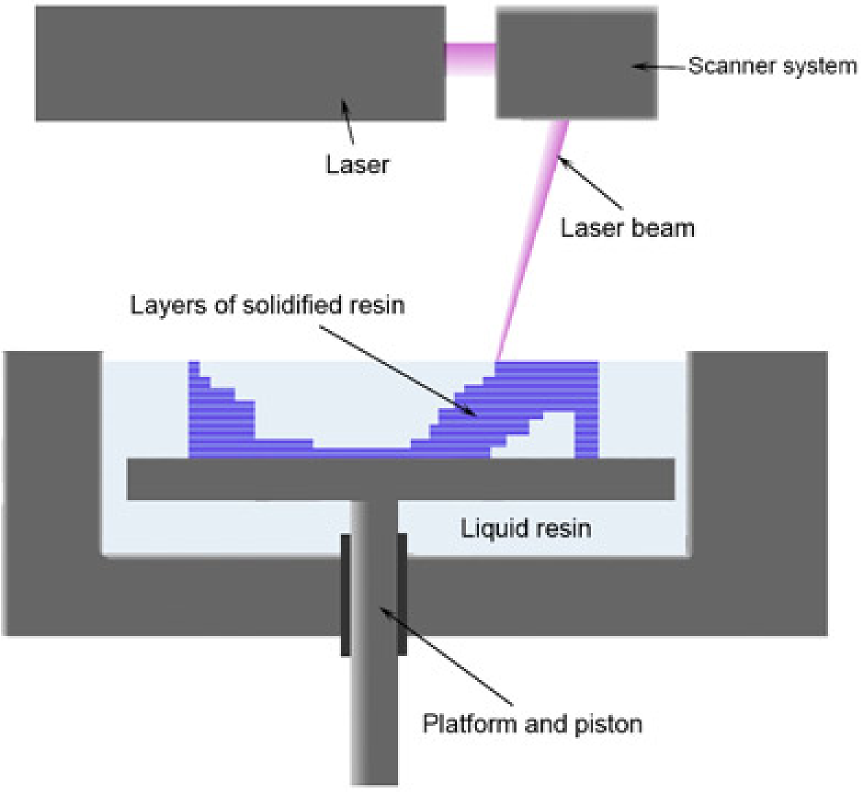


Figure 5: VAT Photopolymerization through a stereolithography machine[6]

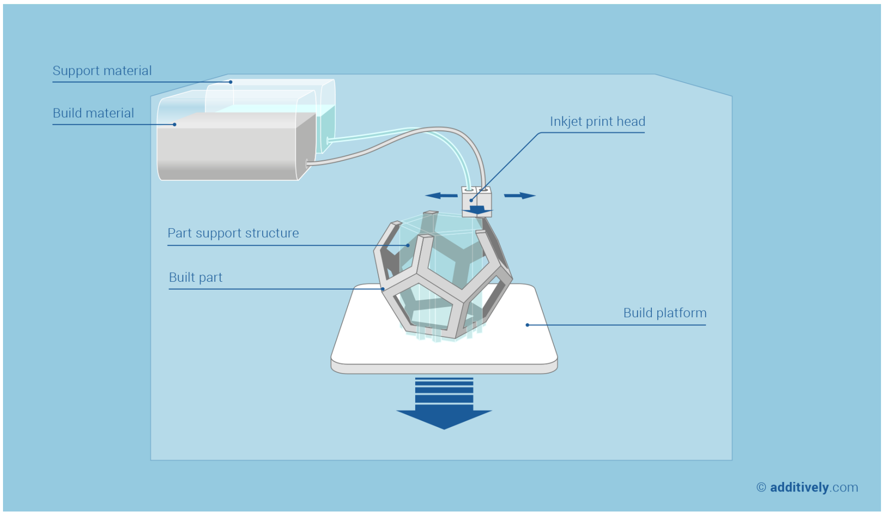


Figure 6: Overview of a Additive manufacturing cell utilizing the material jetting method[7]

however the support processes are different. Usually the machines includes two or more liquid material containers, where one holds the support material which is used to create structures which can be removed after the part is completed. The other containers hold different build materials which can be mixed or dripped individually in order to create certain sections which have different material properties.

These types of printer-type machines are generally cheaper to build compared to other AM machines, especially those that include lasers. They can be built using easily available parts, and are easily scalable through adding more print nozzles in order to deposit large amounts of material quickly. [22] Large part accuracy however isn't quite as good as for the previously mentioned SLA and FFF processes.

One of the major advantages of material jetting is that due to the process of having to expose the entire build volume to UV-light during curing, it doesn't take much longer time to build multiple parts at the same time. This increases the efficiency of creating batches of parts, as long as they all fit within the build volume at the same time.

2.5.5 Binder Jetting

The Binder Jetting method is also a powder bed method, however it doesn't directly fuse the particles together, which makes it a different class than PBF. In a binder jetting machine a powder is spread evenly before having applied a liquid binder through a common inkjet-nozzle similarly to the one used in material jetting. This holds the material together, and when the part is complete it has to be further infiltrated with an epoxy or another metal in order to gain strength.

2.5.6 Directed Energy Deposition

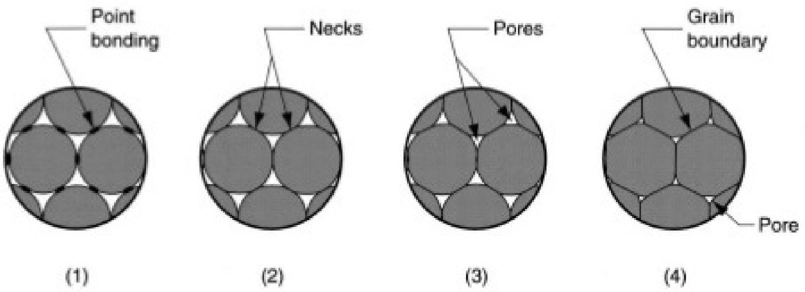
DED is a process similar to that of metal cladding, which is done by melting a material directly onto existing geometry. The material is fed either as a powder or as a wire through a nozzle before it is hit by an electron, laser, or plasma beam after it has exited the nozzle, in turn depositing metal onto the part. See figure 7 for a simple overview of the process. This method can utilize multiple materials in the same part, and is considered relatively fast compared to many other AM methods. The machines which run the DED process are often quite similar or built upon a 5-axis CNC machine, and therefore lends itself to repair or modifications of

Figure 7: Directed energy deposition method for manufacturing an object[8]

existing parts as well. The high rate of build leads to a rough surface finish which typically require subsequent finishing operations in a cnc milling machine when fine surface detail is necessary. Further due to the mechanisms which are similar to welding, the parts must be heat treated in order to reduce residual stresses which occur during the process.

2.5.7 Powder Bed Fusion - Selective Laser Sintering/Melting & Electron Beam Melting

The method of utilizing an aimed energy source for sintering of a powdered material was originally invented by Carl R. Deckard in the nineteen-eighties at the University of Austin, Texas. The machine originally used a laser for the sintering process, but development has shown both lasers and electron beams as viable candidates. The powder which is used can be either metallic or thermoplastic, but generally each machine is made for either one of the two, as there are significant differences in energy requirements to achieve the needed sintering temperature. The process begins by adding a precise amount of finely grained powder in the build chamber by a piston, which is spread by a recoater in order to evenly distribute the powder. The temperature of the build chamber can be held at an elevated temper-



Sintering on a microscopic scale: (1) particle bonding is initiated at contact points; (2) contact points grow into "necks"; (3) the pores between particles are reduced in size; and (4) grain boundaries develop between particles in place of the necked regions.

Figure 8: The sintering process[9]

ature, whilst the power source which is projected on to the powder particles heat them up to between $T_{\text{melt}}/2$ and T_{melt} for Solid State Sintering (SSS), and just above T_{melt} for EBM and SLM. This act of heating the particles form a basis for the sintering process, shown in figure 8, in which diffusion leads to the formation of close to fully dense products as a result.[30] This process is currently becoming more widely used when the designs exhibit high complexity, especially when paired with a wish for lower waste. It is especially true when design demands the use of expensive superalloys, such as inconel 625, which can cost in excess of seven times your typical garden-type 304 stainless steel.[31]

When utilizing the powder bed fusion process for metals the build chamber is normally filled with an inert gas such as argon (for SLS / SLM) or held in a partial vacuum (for EBM), for increases metallurgical stability, and because of the risks of ignition when handling atomized metal powders.[32] The handling of said metal powders also pose a serious threat during transportation and storage, however it is not a new threat introduced by AM as it has been a part of powder metallurgy processes(e.g. hot isostatic pressing, die forming and sintering) for a long time. The last of the patents regarding selective laser sintering that was held by Deckard expired in 2014, and it is therefore expected that SLS will soon experience the same kind of rapid developments that were seen with FFF/FDM™ after 2009. The machines which are under development will never be as low-cost as the desktop variants of FFF, due to the high price seen on Ytterbium & co2 lasers which are used in these

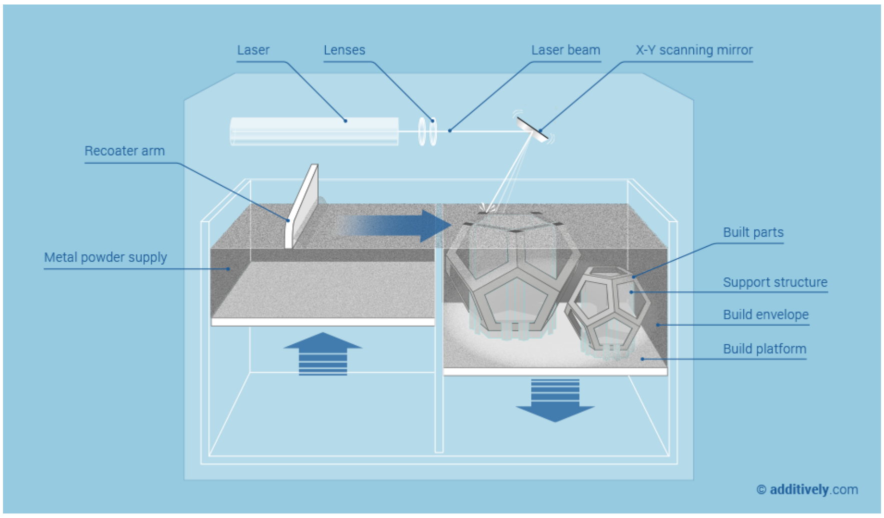


Figure 9: The process of creating parts through powder bed fusion[10]

machines. An overview of the process can be seen in figure 9.

Dawes et al. [33] argues that the cost of powder will be the largest continuous expense when using a powder bed fusion system over time.

2.5.8 Sheet Lamination (Ultrasonic Consolidation)

The sheet lamination method of creating solid objects is very similar to the method which has been used by architects for creating topological maps, where a cardboard outline has been cut and glued together as horizontal layers. The result of such a method is seen in figure 10, however the sheet lamination method generally uses much thinner slices.

The ultrasonic consolidation method automates this type of mechanism and cuts thin slices of metal foils and automatically stacks them vertically through the use of ultrasonic vibrations which cause adhesion between the layers. As the stiction is caused by ultrasonic welding, no melting occurs with the method. This gives the designer new-thought freedom with regards to mixing of materials, as previously metals with dissimilar melting temperatures have been very troublesome to weld together. As such the method has found a niche within embedding electronics into metal parts, and creation of multi-metal heat exchangers.

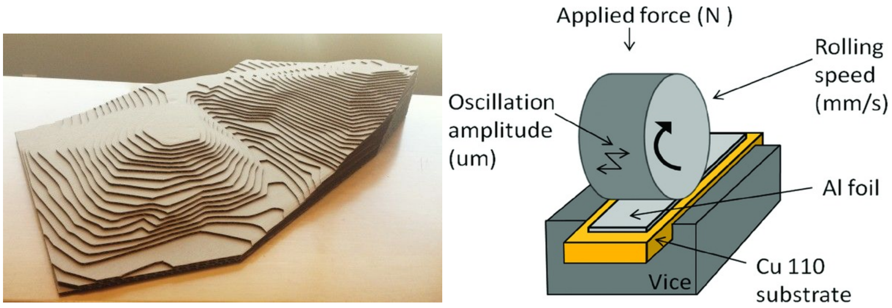


Figure 10: Cardboard sheet lamination and the ultrasonic welding method[11] [12]

2.6 Cost structure of production

In order to compare the costs quotes from producers using a certain manufacturing method against another, it is imperative that we fully understand the cost structure of the processes in use. As such we understand what goes into the pricing of a part, and it improves clarity on which features lead to unnecessary waste and non-value adding activities. This section will try to establish how cost is added to the final product.

2.6.1 Cost Structure Associated with CNC Milling

When CNC machining a part it is normal to start of by cutting a piece of stock into the dimensions required by the part, and then transferring to the milling machine in order to "square up the stock" by milling all sides of the stock - making sure that all sides are perpendicular to each other. A machinist will then have to preprogram the cutting operations, which can become quite time consuming as the complexity of the part increases. With increased complexity the amount of fixturing operations also tend to increase, which significantly increase the time an operator uses on each part. The amount of fixturing positions and operations can be decreased by using more expensive four or five-axis machines, which allows better access to a part from multiple sides.

It can then be seen that the costs which are associated with CNC machining can be summed up as follows(the items seen in **bold** require human operator intervention);

- Purchase of material in length
- **Cutting of stock to correct length**
- **Preparation of stock**

- **Programming of cutting operations**
- **Fixturing operations**
- Cutting operations
- **Machine cleanup**
- Cutter costs - Purchase & wear
- Machine depreciation
- Power consumption

2.6.2 Cost Structure Associated with Additive Manufacturing

When producing an item through an AM machine the cost structure can be seen as quite simple, and requires few parameters in order to calculate the cost.

We start of by using raw 3D Computer-aided design (CAD) Data, which is saved in a standard tesselation language (STL) format. The STL format describes the part through millions of vertices which describe the CAD geometry. That geometry is then loaded into a slicer software, which in turn generates multiple two-dimensional cross-sections which can be layered upon each other, with height spacing according to the accuracy of the printer, in order to create the three-dimensional model. See figure 11 for an overview of the slicer process. This is a very efficient method of creating machine paths, especially when compared to CNC programming, and seldom require more than a few minutes of an operators time in order to start processing and manufacturing a part. The material in use is purchased by weight or volume, which is converted into parts with very high material utilization. When an item is complete it will have to be removed from the machine, a process which varies according to the technology used. In FFF it is a straightforward process in which you simply remove the part and break off the supports used during fabrication. Alternatively they can be dissolved in an alkaline solution, which could add to the cost of operation. With regards to the powder bed fusion processes the removal of a part requires an operator to remove the part from the powder cake. Some manufacturers of PBF machines using nylon-powders also recommend that the machines powder material should be mixed with at least 30% virgin powder in order to set up the machine for the next print.

The costs associated with AM can be summarized as follows;

- Purchase of material by weight or volume

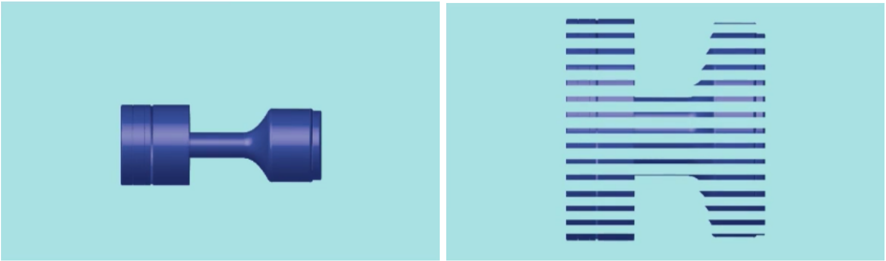


Figure 11: A slicer software is creating two-dimensional layers from a three-dimensional model[13]

- **Programming of additive process - Slicing**
- Additive layer process
- **Part removal**
- **Machine cleanup**
- Machine depreciation
- Power consumption

A comparison of AM and cnc milling is shown in figure 12, in which box length represents how much time is consumed in the process. It can be seen that in the subtractive manufacturing methods, a larger amount of the time is spent on manual labor intensive tasks, such as fixturing and preparation. However once these parts of the process have been done, the method can achieve very impressive production speeds, and can continue to produce parts with high precision and accuracy almost non-stop. AM machines however utilize most of their time in a fully automated state, where no human machine intervention is required. This state of adding layer upon layer is however much slower than the cutting actions mentioned. This leads to long runtime per part, but at low start-up cost. The increased level of automation can also lead to cost savings from the reduction of human errors which are associated with the programming, fixturing and probing steps of CNC machining.

2.7 Previous Work on Price-Efficiency of Additive Manufacturing

In 2003 cost estimation of rapid manufacturing (previously used naming convention for manufacturing of end-use parts through rapid prototyping) showed that the AM methods SLS, SLA and FDM™ could be used as an alternative to injection molding for a very small plastic part (3,5gram).[34] The costs from AM was calcu-

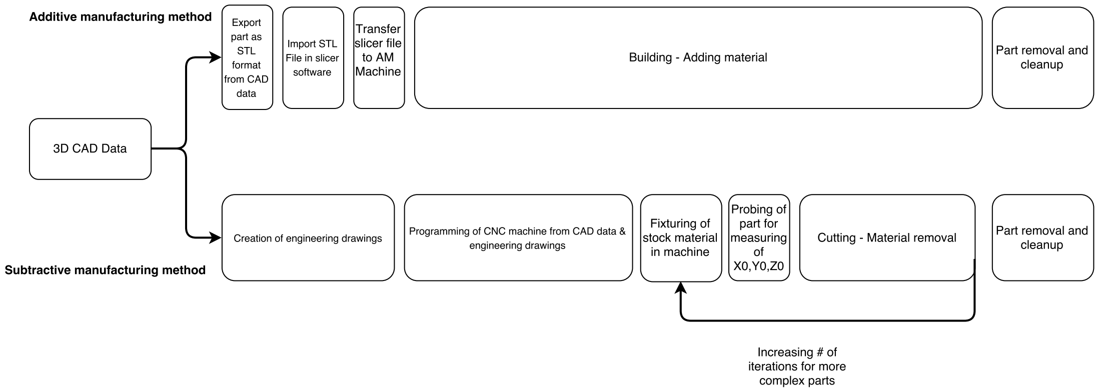


Figure 12: The process of creating parts through additive and subtractive manufacturing processes

lated and compared to a quote on injection molding tooling costing 32100€ with unit costs of 0.23€, and showed that SLA and FDM™ was a viable method up to 6000 units, whereas SLS showed promise up to 14000 parts. Faults can however be found in that the analysis takes basis on no reuse of powders in the SLS machine, and that it doesn't take into account that SLA is a method not suited for end-use parts.

Ruffo et al. [35] built upon the work in 2006 and further improved the model for the SLS process only, and estimated a new break-even point at 9000 parts. They also identified that the amount of units produced fits better in between low and medium volume production, and that the AM pricing model is not as flat as expected.

The injection molding alternative would however never work for the very low volumes investigated in this thesis, and would have costed more than 1500€ per 3,5gram part if you only needed 20.

3 Methodology

As this thesis aims to verify if AM methods can be used efficiently for producing small volumes I have chosen to structure it as a case study, as the method is well suited to understanding complex situations. The thesis combines qualitative and quantitative methods to enlighten the cost and usefulness of additive manufacturing. According to Charles Schell [36] "the case study is unparalleled for its ability to consider a single or complex research question within an environment rich with contextual variables. Observation, experiments, surveys and secondary information (archival) have the advantage of producing sets of independent and dependent variables suitable for quantitative analysis: The case study is best suited to considering the how and why questions, or when the investigator has little control over events."

With this in mind I have combined semi-structured in-depth interviews with users, retailers and manufacturers of AM technology, with cost quotes on parts created through subtractive and additive manufacturing methods.

In an extremely rapidly evolving business I have tried to keep all sources used as new as possible, due to research on the subject quickly becoming obsolete.

3.1 Interview Guide

For all interviews there was created an interview guide prior to the interview taking place. The interview guide was specifically created for each interviewee and helps the interviewer cover all the aspects which were planned in advance.

For the interviews with machine manufacturers the questions regarded how they work together with other industry partners to achieve common goals, and help guide progress in the value chain. With the retailers & machining companies it was more interesting to discuss the market scenarios they see evolving, how the new customers would be found and how they see the cost trend of additive systems moving as it becomes more widely used in the market.

3.2 Evaluation criteria for manufactured parts

In order to capture the multivariable nature of manufacturing, four parts have been chosen to be evaluated in this thesis. The evaluation will be done on a basis of price quotes obtained from established manufacturing companies, for both CNC & additive manufacturing methods.

The four parts are categorized into two plastic and two metal parts, where each part features unique challenges associated with them. This is done as parts made through AM can be produced in a single stage, whereas CNC machining in many cases require multiple setups together with process planning, especially when parts become more complex in their geometries [22].

3.2.1 Complexity

As a CNC machinist you will have to evaluate all of the geometries which a part comprises of, and the features all add to the cost of creating the product. A good designer will often take this into account when drawing a part. The concept of taking production method into account is often called Design For Manufacturing (DFM), and it is generally used in order to reduce cost of a part. It can however be seen as a method of allowing the designer less choice on complexity as a way of achieving that reduced cost. When categorizing the parts according to their complexity it can become easier to evaluate which features add to the cost of CNC machining, and can indicate when a change-over to additive manufacturing can be a good choice. As such the parts that are featured in this thesis exhibit a varying degree of complexity by choice, and it can be seen that part I is less complex than part II, and that part IV is more complex than part III. The increasing complexity does however not transcend between plastic & metal parts. As such part III is not necessarily more complex than II.

3.2.2 Quality

According to ISO9000:2015 quality is defined as "degree to which a set of inherent characteristics fulfills requirement", a broad definition catering to any and all processes. If we instead look at ISO8402:1994, which is the predecessor of ISO9000, catering more towards production, it is defined as "the totality of characteristics of an entity that bear upon its ability to satisfy stated and implied needs."

It can be seen from the definition that it is the objects ability to satisfy the requirements or needs which are the key to achieving "quality", and as such quality is neither perfection nor anything under the necessity.

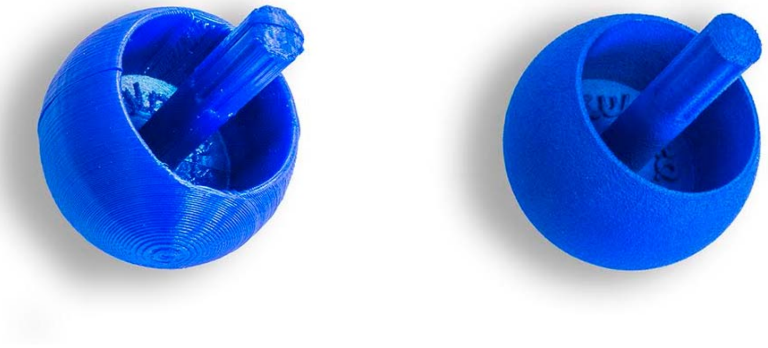


Figure 13: A comparison of the surface quality of a part manufactured with a low cost FFF machine versus that of a high-end SLS machine[14][15]

With regards to AM it is a commonly known fact that AM produce objects with an inferior surface finish, and that pieces made with consumer devices often have problems with layer delamination(reduced strength between the vertically stacked two-dimensional layers). As these machines are what people generally have access to, it should be noted that AM is often judged based on the output of a sub-5000$ dollar machines, and then compared to parts created through cnc machining, often with no regards to the cost of the cnc mill (100,000$ USD and upwards).

This leads to an unjustified image of AM being perceived as lower quality, however that isn't necessarily the case, unless for the tribological reasons mentioned in 2.5.1. In figure 13 the differences between parts manufactured through a low-end FFF and high-end SLS system are shown, and on this basis only items produced through high-end systems have been evaluated in this thesis.

With CNC machining achieving a low average roughness value R_a is generally considered a trade-off between speed and productivity, where perfecting the surface finish requires significant time. Most cutting operations lie within 0.8—12.6μm, whereas a raw SLS part can have a roughness of around $5-10\mu m$, and shot peening/bead blasting(seen in the figure of CNC machined parts) lowers this to around $3-5\mu m$.[37]

In this thesis the quality of an object is accepted as good enough if it is able to withstand the necessary loads, and performs its intended function.

3.2.3 Cost

The parts will be evaluated according to their costs based upon cost quotations achieved from industry partners. Due to the very low frequency of AM systems available in Norway, most of the data has been acquired from companies in other countries. As the manual labor required in order to run a AM system is considered very low, it is assumed that the costs of personnel is a small part of the total costs involved with having objects fabricated. Most of the costs associated with the additive process can then be accounted by machine depreciation in a very quickly changing market, together with material costs and power consumption.

When comparing the price quotes all prices are calculated into 2016 US Dollars, based on currency prices taken from the same point in time, in order to remove any variance introduced from fluctuations in currency. The US Dollar is chosen as the used currency based on the dealings in a globalized market, and that commodities such as the raw materials for the processes evaluated in this thesis are commonly traded in dollars.

When evaluating prices coming from countries spread around the world, the prices will be seen in context with the countries "GDP Per Capita" at Purchasing Power Parity as a guideline for the associated costs with having an item produced in said country. GDP Per capita does not necessarily relate directly with production costs of a certain country, however Bhagwati [38] argues that a strong correlation between cost of services and GDP per capita can be found, thus showing at least correlation towards worker wages for CNC machinists. The data for GDP per capita has been found in the raw data acquired from The World Bank's 2014 indicators.[39] With limited availability of companies that provided price quotes it was not always possible to find companies from the same country which provided both additive manufacturing and CNC machining services. As such price quotes from neighboring countries with similar GDP Per Capita has been used as a comparison, as far as this was possible.

3.2.4 Repeatability

When evaluating whether a method can be used in a industrial environment we have to make sure that the method creates parts which are the same every time they are produced. Repeatability and accuracy is not the same, and in most cases a good repeatability is more important than high accuracy. An example of this could be; a cube, which in its 3d cad data has dimensions of exactly 50x50x50mm. After producing twenty units we measure them, and they all measure 50.1 ± 0.1mm. The next time we produce them they measure 50.2 ± 0.05mm. In this situation we can see that the deviation consists of an offset and a tolerance. The offset deviations are often much easier to handle, due to the fact that we can measure and resize the parts, or recalibrate the machine, to get the dimensions wanted. The tolerance part is a product of inconsistent production parameters such as the build plate temperature, build-volume temperature, extruder or laser power, varying material shrinkage, etc, and as such they are much harder to control. According to Ville Matilainen in his thesis "Benchmarking of laser additive manufacturing process"[40] most of the machines which are built upon the powder bed fusion method have very stable build parameters and as such low or constant offsets and tolerances. Real world testing of the FDM™ / FFF process done by stratasys in 2008 on 108 sample parts showed that the dimensional accuracy was within $0.04 mm/mm$ based on a two-sigma or 95% certainty level[41]. Their newest system, the fortus 450mc, is stated to have a dimensional accuracy of $0.0015 mm/mm$ which seems possible given the technological advances since 2008[42]. On basis of the findings in these studies i have concluded that the repeatability of the methods and machines are good enough for the production of the parts in question.

3.3 Quote retrieval

In order to obtain prices for the parts from representative manufacturers, a Request For Quote (RFQ) was sent to the manufacturers. The manufacturers were all given the same information in order to produce the quote, and were notified that there was no rush in completing the parts, thereby removing any expeditation fees the companies could add on. The companies were as far as possible not told that the parts would be used as a basis for comparison between technologies, as this could result in them altering their pricing. In some cases however, interviews with personnel at the company had been completed prior to receiving quotations from them. This could lead to them favoring the processes that they perform, which could skew prices. It is however impossible to take into account that these companies could have changed their prices in order to alter the results in such a way that they would benefit from it. Further the companies were told that the quote would be a final offer without any further discussion with regards to price, pushing them to give their best offer immediately rather than a starting point for negotiating.

As per the quality requirements mentioned in the Quality section on page 22 the companies utilizing the CNC process were told not to verify tolerances further than per model specifications. This is done because the verification process is time consuming, and normally done in order to prove to the customer that the part is within specification. With CNC milling it is expected that the finish and dimensional accuracy is automatically better than for the AM processes, and as such the surface finish and accuracy of the machining process was "lowered" down to a level which is closer to what current additive processes can satisfy.

4 Results and Discussion

4.1 Additive methods evaluated

Through my interviews it has become clear that some of the AM methods are unsuitable for the production of end use products, as they are primarily focused on the act of prototyping fit & form function. This has lead to a much needed narrowing of the focus area for the thesis, and two methods have been found to be best fit for production of end use parts.

As all of the methods utilizing UV-curable resins exhibit increasing hardness combined with brittleness from exposure to light over time, they are prone to cracking and self disintegrating within relatively short durations of exposure to sunlight.[43] This mechanism is called photodegradation, and affects all photopolymers. Based on this the methods of stereolithography and Multijet modeling have been omitted from further inclusion in the thesis.

Ultrasonic consolidation has been considered as being not mature enough to provide insight towards costs due to how few companies are using it, and that most of the companies that do, are using it is towards creating injection moulding tooling, or integrated electronics, which is a different subject than what this thesis focuses on.

Further most binder jetting processes require significant post-processing in order to infiltrate them with either epoxies or metals which causes them to increase in strength. As such the method does not provide the same set of advantages that are found in the most optimal additive manufacturing processes, where only minor support removal and/or heat treatment is needed.

The process of Directed energy deposition (DED) has a lower resolution, and cannot produce as complex geometries as its alternatives, and is therefore not proposed as a method of creating end-use parts directly. It may however still be a very good method, when used in combination with CNC machining, as seen in the hybrid manufacturing cells, where high output rates combined with finish machining may be a good alternative.

The unique subgenre of Powder Bed Fusion processes utilizing an electron beam for the powder melting is seen as a promising method which is marketed as being multiple times as fast as their laser counterparts, however as their method only works with Titanium and Cobalt-Chrome alloys at this point of time, it seems unreasonable to include it in a comparison which is done for aluminium (and plastic) parts.

The methods which will be evaluated are then narrowed down to;

- Material extrusion (FDM™ / FFF) and powder bed fusion (SLS) for the production of plastic parts
- Powder bed fusion (SLS/SLM) for the production of metal parts

4.2 Evaluated Parts

In this section I will describe and elaborate on the parts which are used to evaluate the cost-performance of additive manufacturing. By describing the challenges associated with each part we can gain a clear understanding of the features which contribute to increased cost. The parts have been chosen due to their unique characteristics and features. All parts are in use today in different student projects at the University of Stavanger, and have been manufactured through methods which will be described in the following subsections.

4.2.1 Part I: Plastic Thruster Housing

The plastic thruster housing seen in figure 14 is one of eight thrusters onboard UIS Subsea's autonomous underwater vehicle named "Loke". The vehicle is a one-off project created in order to compete in "euRathlon", an outdoor emergency-response robotics competition, and as such it qualifies as a low-volume project. Four of these thruster housings are used per vehicle, and they are the single component which holds the electric motors that provide propulsion in place. The housing walls are convex in order to provide optimal pressure gradients along the sidewalls when the propeller is spinning. The use of a internal convex shape forces the use of three-dimensional machining strategies, and special undercutting tooling, which make the part fairly advanced to machine through traditional methods. A cross section of the part can be seen in figure 15. As a minimum the part requires three fixturing operations in order to reach all places in a traditional tri-axial milling machine. With the use of a multi-tasking machine, the number of fixturing operations can be reduced and it makes it possible to use more standardized tooling through

Figure 14: An overview of part I: thruster housing, shown with transparent propeller(Part II) and DC outrunner motor.

turning-strategies instead.

The part is originally crafted from ABS plastic through FDM™ in the Stratasys Fortus 450mc located in the 3d-printing lab at UiS, as this was seen as the most viable solution available for the students. An alternative to the ABS material could however be the engineering plastic Polyoxymethylene (POM), which is better suited to the machining processes.

4.2.2 Part II: Plastic Propeller

The plastic propeller seen in figure 14 is also in use on the UIS Subsea AUV, and was produced in the same additive manufacturing system as the housing. As the vehicle uses eight thrusters, there are currently eight identical propellers in use. The designers of the system tried finding standard propellers which would fit the electric motor, but none of the available propellers had the necessary internal diameter. The blades' unique NACA airfoil shape seen in figure 16 paired with very thin walled sections lead to very low MRR which are constrained by the excessive vibrations or chatter caused by the cutting actions in a CNC machine. Further the part requires a minimum of two machine setups with tri-axial milling, which can

Figure 15: A cross-sectional view of part I: the thruster housing

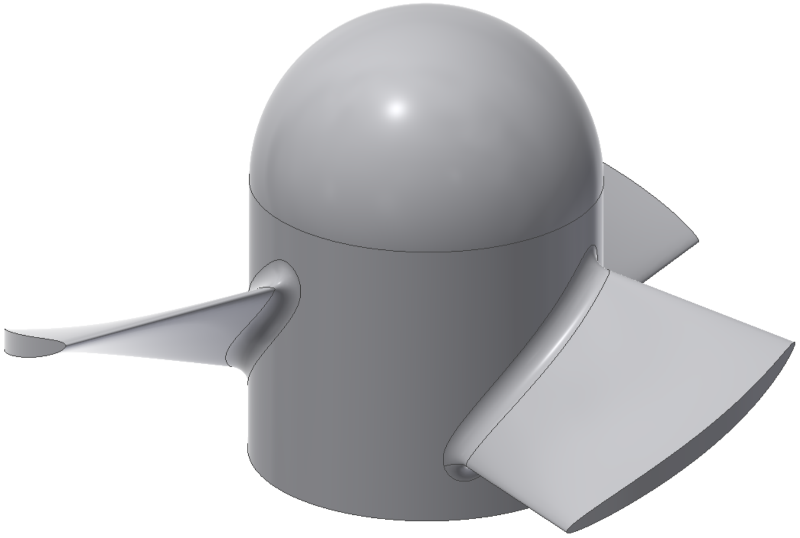


Figure 16: A side view of part II: the auv propeller. Note the thin walls at the ends of the NACA airfoil blade, together with the varying blade pitch

be reduced down to one through creating it from round stock in a multi-tasking cnc machine.

4.2.3 Part III: Metal Race Car Front Upright

Part 3, the racecar front upright is a part that is taken off the University of Stavanger's "ION Racing" Formula Student teams' Embla. Embla is an electrically powered single-seat race car created in order to participate in the 2016 Formula Student race competition at Silverstone, England. The front upright is a structural part of the front suspension, and carries the front wheels, and brake assembly. As such there are considerable forces acting upon it through turns, bumps and during braking. The part, of which there is two on the car, is machined out of Aluminium 6082-T6, which is a aluminium-magnesium-silicon alloy, age hardened to the T6 state. As such the alloy has a yield strength of 270MPa, and Ultimate Tensile Strength of 330MPa[44] and any additively manufactured alternative to the part must exhibit similar material properties. Figure 17 shows the engineering drawing of the upright. As seen from the drawings the part is fairly large with its 244mm edge-to-edge, which is just below the maximum build volume of most commonly available metal AM systems. The part is not considered a complex part as all of the profiles and

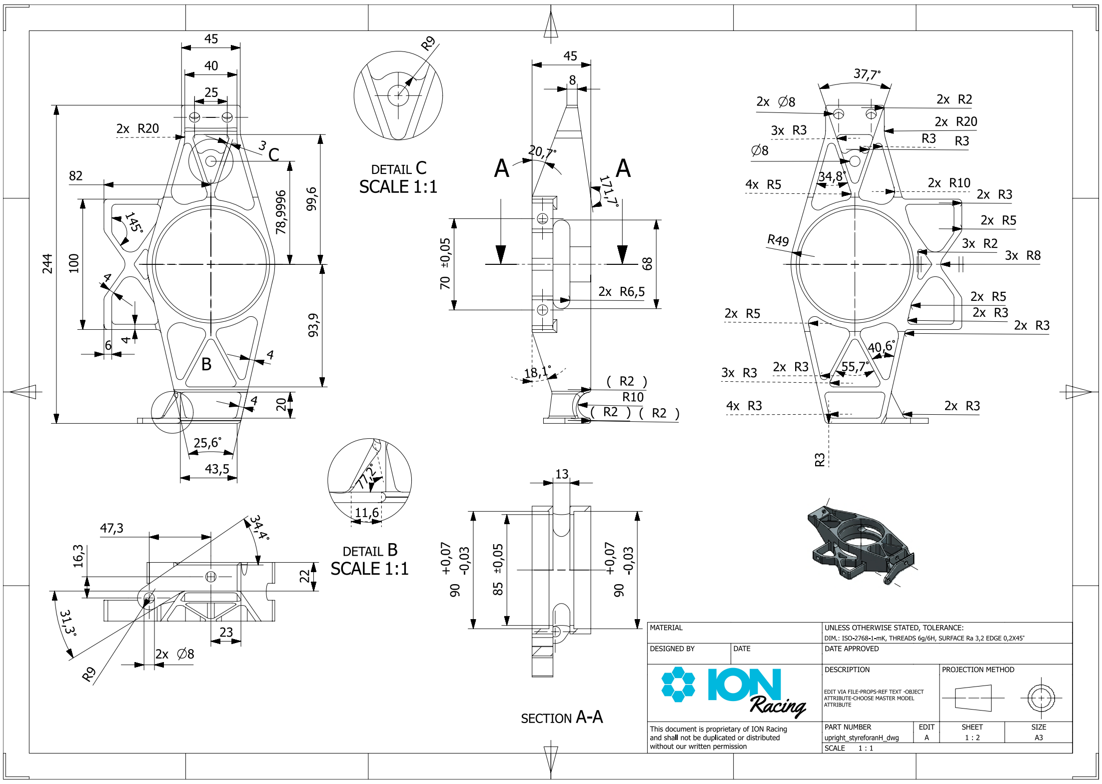


Figure 17: Engineering drawings of part III: The metal race car front upright[16]

features are two-dimensional in their shape & form. This makes the part millable through two relatively simple setup operations in a three-axis machine, or one setup in a five-axis machine.

4.2.4 Part IV: Metal Race Car Rear Suspension Bracket

The rear suspension bracket is one of the major structural parts on the rear suspension setup on the ION Racing car. It is designed to be as light as possible whilst still retaining the strength to withhold the rear damper setup. It is a highly complex part which is almost impossible to manufacture in a three-axis CNC machine, and requires the use of minimum five-axis machining together with three-dimensional milling strategies. The very small internal radiuses creates a need for extra long milling tools in order to reach the pocket corners, which leads to high costs of machining. The parts geometry can be seen in figure 18. The two brackets on the car was originally planned to be additively manufactured, but in the end it was crafted through a manual lost wax casting method with the help of a local jeweler, but could just as well have been machined or printed.

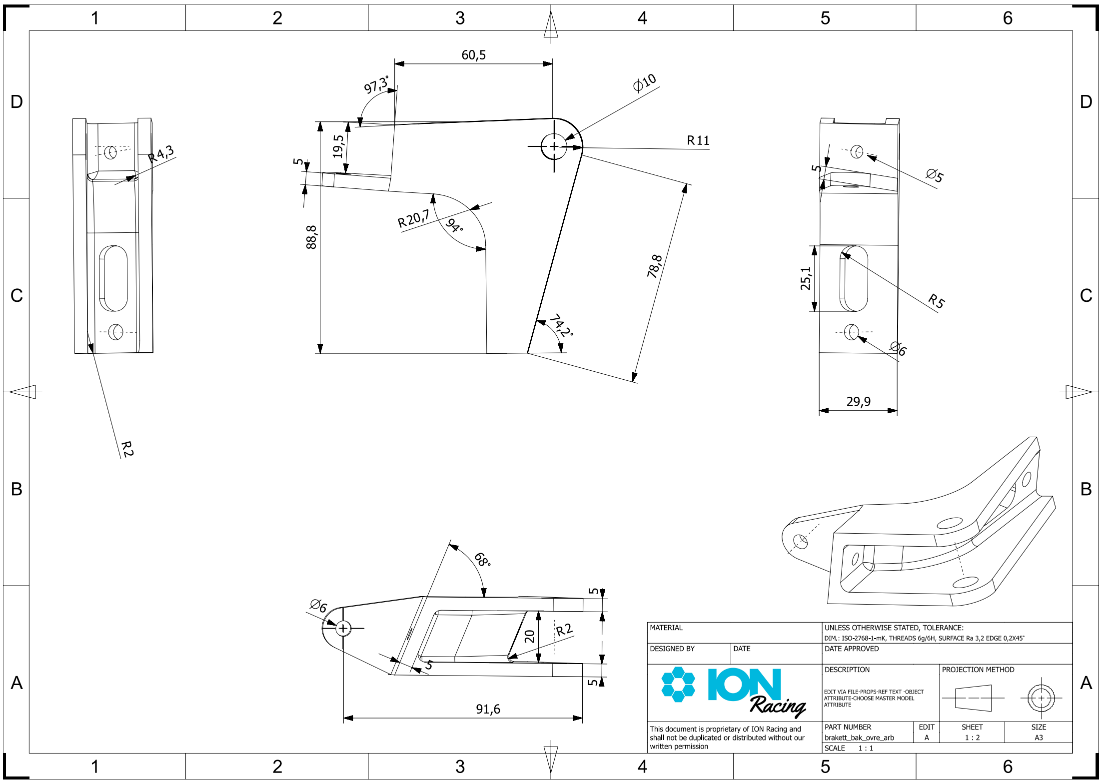


Figure 18: Engineering drawings of part IV: The metal race car rear suspension bracket[17]

4.3 Cost Comparison of AM and SM methods

The following section will try to give insights into the costs of having items produced through additive and subtractive methods. In the following graphs each manufacturer is shown with an individual series. If the same country is listed twice or more, this shows that multiple manufacturers from that same country offered to produce the item. In the cases where this is seen a "normalized average" is used instead of a normal average. This normalized average is calculated by first averaging all of the manufacturers in one country, prior to combining them with other manufacturers data. This makes it so that each country is weighed equally towards the average, no matter how many of the manufacturers they have.

4.3.1 Part I: Plastic thruster housing

It has been estimated from the interviews that it can take up to ten hours of programming & readying a multi-tasking CNC machine in order to produce the thruster housing. After initial setup each part should require approximately 1 hour to complete after starting series production. Material costs of each part is approximately 5 USD/part when purchasing round bar stock, compared to 70 USD/kg for the powder bed fusion processes, and around 280 USD/kg for the FDM™ process. With a part volume of 129.5 cm^3, material density close to $1(0.93-1.04\,g/cm^3)$, and a powder-reusability ratio of 0.7 for PBF this calculates into raw material costs of 13 USD/part and 36 USD/part respectively. In figure 19, the prices for the production of part I, through both SM and AM methods in multiple countries are shown.

As seen in the graph P1-CNC the pricing of CNC services fluctuate significantly according to supplier location, varying from a unit price of 1988USD when producing a single unit in a high-cost country down to 144USD at it's cheapest when producing 20 units, in a low cost country. Major differences in pricing strategy is also seen as not all of the manufacturers employ a high initial price, which could signify that the manufacturer is either very good at standardizing their machinery and machine tools for quickly changing between jobs, or that the manufacturer is willing to take a loss at the first parts in order to secure later production.

Some level of correlation between the Norwegian, UK and Chinese CNC pricing levels is found when purchasing five units. The average price of the two Norwegian producers were compared to the price received from the UK and Chinese producer, and prices were consistent towards the GDP Per Capita of respectively 65.5, 40.2, and 13.2k USD[39]. USA's GDP Per Capita is 54.5k, and does not coincide with the seen production costs of part I. It is however estimated that the high spread of wealth distribution in USA could lead to the GDP Per Capita not being the optimal cost indicator, as most production jobs are considered low-income.

For the production of parts through additive manufacturing, the pricing is seen to be relatively flat, with FFF seeing a larger reduction in price than its PBF counterpart. The average price of having produced one thruster housing through FFF is 256USD, and drops down to 188USD/unit at 20 units volume. With PBF the numbers range from 147USD/unit down to 125USD/unit.

The cost of having 1 unit produced by AM is in average 180USD, compared to 730USD in the CNC process, with the difference becoming smallest at 20 units, where the average price is 144 and 315USD/part.

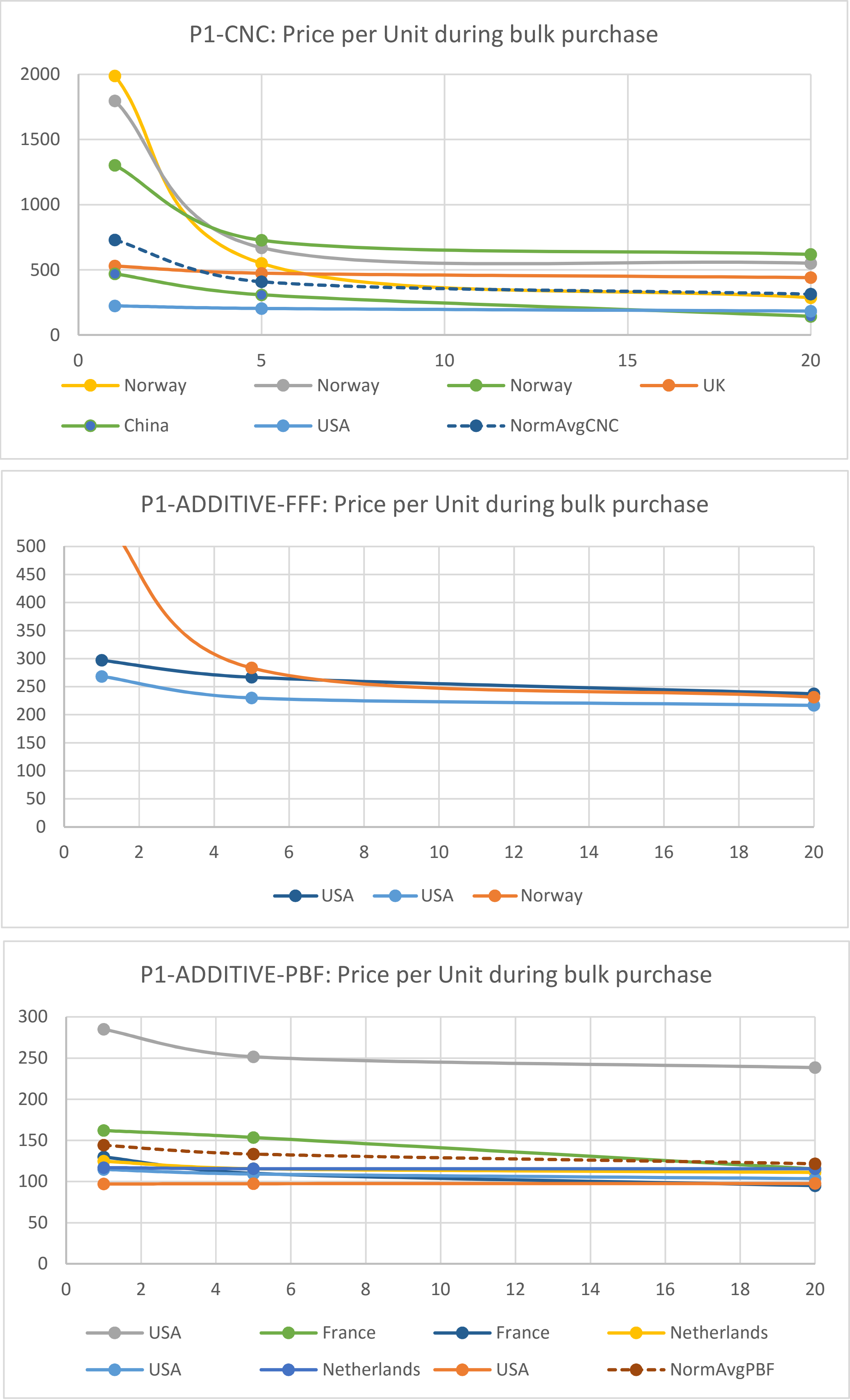


Figure 19: Cost of having part I produced at multiple volumes through SM and AM

4.3.2 Part II: Plastic Propeller

For the production of the propeller similar situations as seen for the thruster housing are found. Preparation and machine setup was estimated at up to eight hours, with additional runs taking up to 1.5hours, due to low feedrates achieved on the thin-walled sections. The material costs are calculated equal to that mentioned in Part I, but with a part volume of 14.1 cm^3 the material unit costs are 1USD/Part for PBF and 3.5USD/Part with FFF.

The CNC method in average(normalized) starts of at 547USD and tapers down to 180USD/part, whereas the average cost of producing one unit through AM is 40USD, down to 31USD/part at 20 units.

The lowest price found for CNC machining was 39USD/part at 20 units in China, and for AM it was through the PBF method in the Netherlands at 13USD/part.

No correlation between a countries GDP Per Capita and cost of production through AM methods are found. To a certain degree the correlation between CNC costs and GDP Per Capita is seen in figure 20, but not to an extent that surpasses the fact that work hours are notably more costly in high-GDPPC countries.

4.3.3 Part III: Metal Race Car Front Upright

The front upright is quite large with a part volume of 188.3 cm^3, but exhibits relatively low complexity. Consequently setup time is found to take up to 15 hours. Removal of large amounts of raw material is needed in order to create the final product, which has a final weight of around 500 g. The original stock for CNC milling must be at least 3800 g which accounts to material costs of approximately 30 USD for the CNC process, and gives the part a Buy-to-fly Ratio of 7,6. With the small pockets reducing the cutter size, each run is estimated to take up to 3 hours. With additive manufacturing the raw material cost is found to be around 75USD/part, a relatively small contribution towards the total price, when the average price of having one unit produced through AM is 2067USD. This average price falls down to 1405USD/part when creating 20 units, versus the normalized average of 555USD/part for CNC machining. One-of production through CNC had a normalized average cost of 1241USD, showing that even first part production including setup is of lower cost than AM for this part.

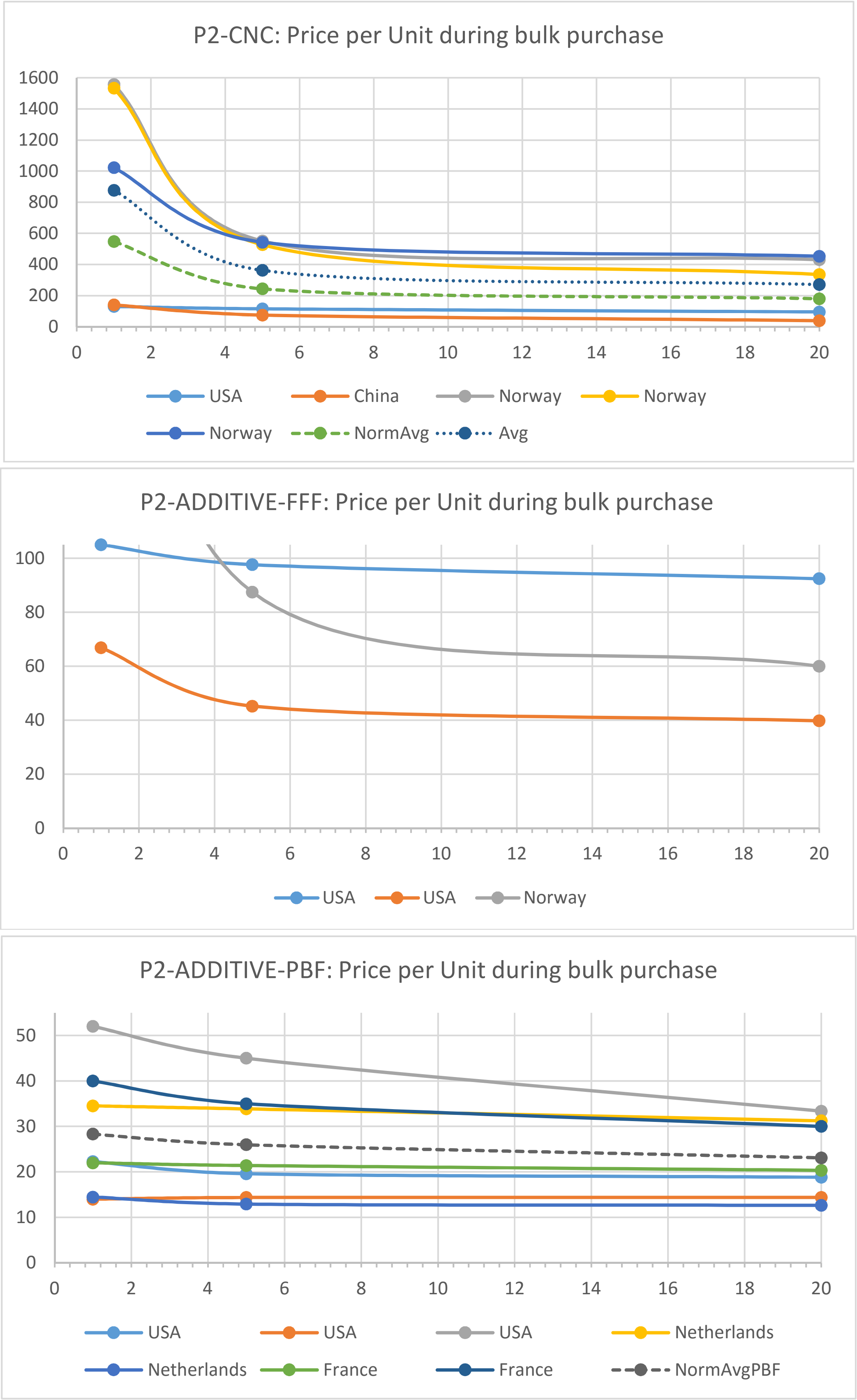


Figure 20: Cost of having part II produced at multiple volumes

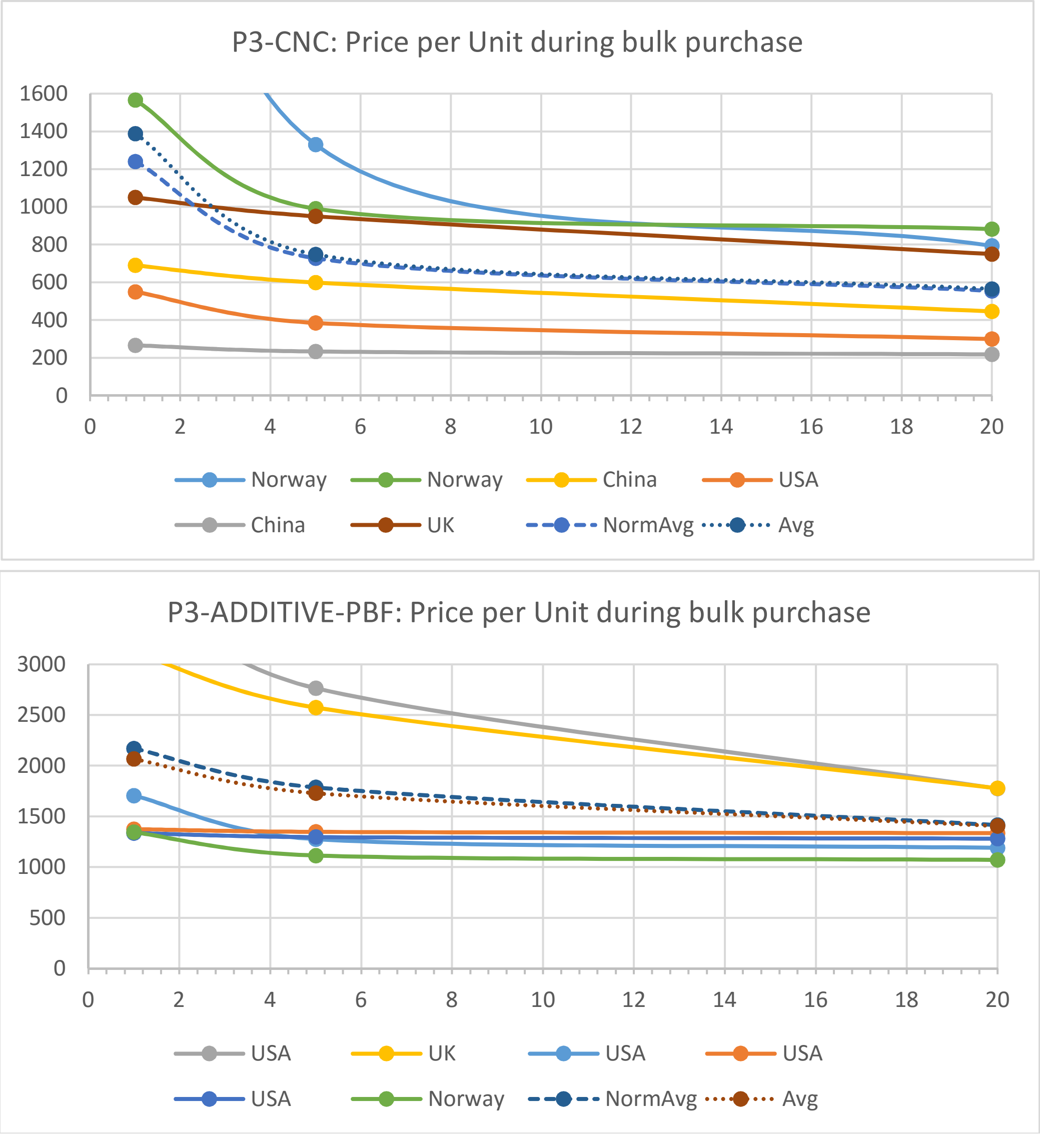


Figure 21: Cost of having part III produced at multiple volumes

Figure 21 shows the development of prices throughout the production volumes, with Norwegian CNC prices starting off at average 2885USD (above graph area) per unit, down to 838USD/part for twenty units. Again the American manufacturer sticks out from the crowd with its low costs, comparable to that of the Chinese businesses.

4.3.4 Part IV: Metal Race Car Rear Suspension Bracket

Production setup time for the rear suspension bracket is estimated to take up to fifteen hours. With a relatively small volume of 44 cm^3, and high Buy-to-fly Ratio of 13.7, each part takes around 30 minutes to complete. As such the CNC pricing starts

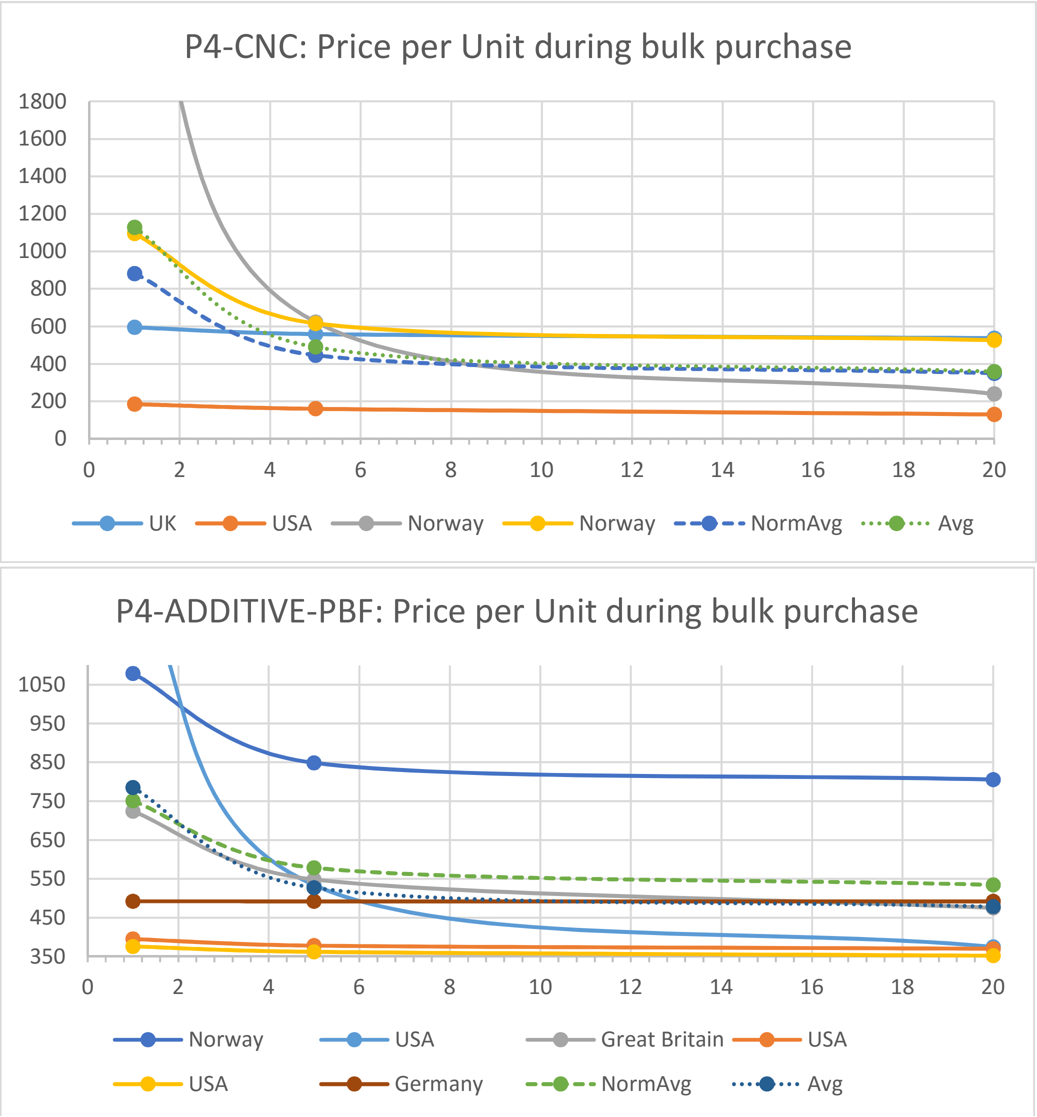


Figure 22: Cost of having part IV produced at multiple volumes

of at Norwegian average price of 1865USD, down to 383USD/part. For the additive counterpart average prices between 1351 and 352USD/Part has been found. The normalized average price of having 20 units produced is 535USD/part, compared to 358USD/part with the traditional method.

As seen in figure 22, the pricing strategies employed by the companies significantly impact the price. Again; companies employing flat pricing curves are probably hoping for the customer to procure as many units as possible, which improves their earnings compared to those that employ high initial pricing which tapers off quickly.

4.4 Drivers for Implementing Additive Manufacturing

Apart from the direct costs incurred from production, AM can be seen to have many other benefits which contribute towards lowered life cycle costs, not as easily quantifiable through direct comparison. These benefits may in many cases directly reduce cost from reduced assembly time, whilst in other cases it might only be seen as benefiting the environment.

This section will aim to introduce the reader to some additional traits that could lead to increased adoption of AM.

4.4.1 Competence Requirements

The training program for operating a CNC machine in Norway, is currently two years of secondary upper school, combined with a 24 month long apprenticeship. As such the act of CNC machining requires significant knowledge of the processes, about the materials, and about the unique & sometimes proprietary machine programming languages (G-code, M-code, Mazatrol etc). Many machine shops currently use only one machine manufacturer for all of their CNC machines, so that an operator can move between multiple machines. Said differently, CNC machines from assorted manufacturers are so different in their control & programming that it would take a long time for an operator to become familiar with using another brand.

In contrast most operation of 3D-printing machines require significantly less technical competence, and would reduce the need for trained personnel. This could lead to either reduced workforce, or a workforce that could be utilized for more demanding tasks. For engineering companies, this means that part of the production process could be done in-house, giving the engineers almost instant feedback to the parts designed, which in terms can reduce the design time, and time to market for new products.

4.4.2 JIT - Just In Time

Just In Time (JIT) production focuses on the savings provided from receiving what is needed at the time it is needed. Examples of this can be seen in modern car factories, where the production of seats & dashboards are outsourced to third-party manufacturers, and delivered JIT. This act of receiving the needed parts just prior to assembly reduces the need for storage capacity and thereby reduces overhead costs associated with producing the vehicle. Additionally when all parts are created based on fulfilling individual orders, there will be no "red chairs" left over as production of next years model begins.

Richard Morris, Vice President of assembly at BMW's production plant in Spartanburg, South Carolina, states that BMW receive 82% of all parts Just-In-Time, with no more than a two hour inventory available, in order to trim costs in it's production plants.[45]

With AM there is no penalty for changing the production from one type of part into another, as long as they are of the same material, and of reasonably equal size. This leads to an important point with regards to how additive production processes fit together with a JIT methodology. AM processes are well suited towards producing parts used in a facility utilizing JIT due to the rapid to no changeover time in its production, and could with increased efficiency, act as an internal buffer should pieces not be received in time for the assembly process. This leads us to the next important area of consideration;

4.4.3 High Variation & Mass Customization

Due to the fact that there is low or no cost associated with altering the produced part, AM can introduce new market potential through high variation & mass customization.

Jiao et al. [46] states that a customized product increases profits by increasing customer-perceived value. They propose a method of utilizing individual building blocks in a traditional mass production environment, which can be put together in order to create a complete and customized product. However they also state that the process must be very carefully planned in order to be profitable.

With additive manufacturing a company can accommodate for individual customization through relatively simple computer tools, picking and placing components, or even self-designed parts, which can be built in a single stage, removing or reducing the need for assembly processes. With such processes the customers' needs can be even better catered to, which could provide that last step of differentiation away from your competitors.

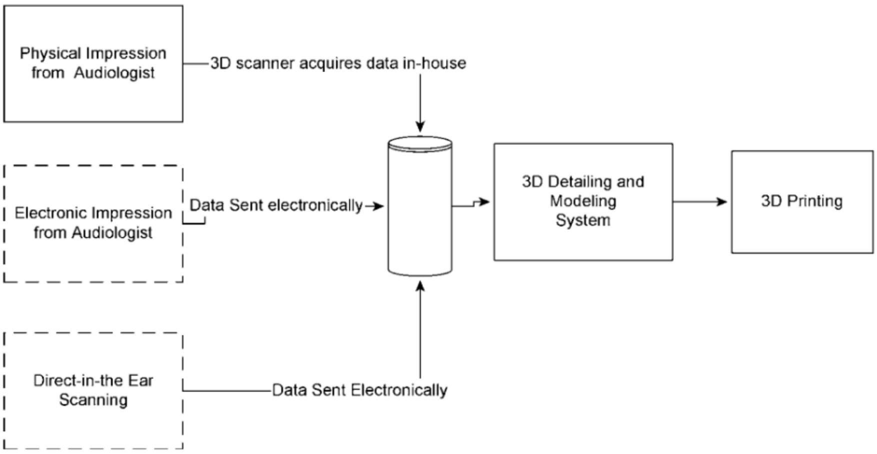


Figure 23: Process overview for additive manufacturing of hearing aids at Siemens Hearing Instruments Inc.

Masters et al. [47] notes that the hearing aid industry is probably the industry which started utilizing AM in large scale first, due to the explicit needs of manufacturing each in-ear hearing aid to perfect fit, according to each individuals unique ears. The process currently in use by Siemens Hearing Instruments Inc. can be seen in figure 23. The implementation of this process has led to increased customer satisfaction, as fit issues are minimized compared to the previously used process where a craftsman would individually create one-offs from a molded impression of each patients ear.

4.4.4 Possible Disruptive Effects on Existing Machining Markets

Traditional machining companies currently earn a substantial amount of their profit through the hours used for machine-setup and preparations. With the maturation of AM engineering companies could use it as a cheap alternative for testing of form, fit and function of the first part, prior to accepting continued production. As such initial "prototyping" or first run production with AM may significantly reduce the number of failed parts produced by machine shops that receive faulty engineering drawings, or poor design choices. This act differs a little with todays prototyping mechanisms, in which the products are often prototyped through AM but produced through other methods, and as such they don't employ the same set of constraints throughout the product development cycle.

A second situation that might evolve, and the one which is probably the most reasonable to assume, is that machine shops will invest in additive manufacturing

Figure 24: Topology optimized skeleton frame motorcycle, by airbus APWORKS[18]

machines alongside their CNC machines. In this situation additive manufacturing methods can be used for the production of near-net-shape parts, which can be finish machined to a mirror finish, whilst achieving the necessary tolerances for shafts, bearings etc. Unique machines combining the methods of both Additive & Subtractive manufacturing methods have begun to be created, as shown by DMG Mori's "Lasertec 65 3D" which combines the Direct Energy Deposition method with 5-Axis CNC milling.

4.4.5 Geometrical Freedom & Bio-mimicking

The traditional approach to designing a part begins by applying the manufacturing constraints to your design, and trying to design your parts around the manufacturing system. With additive manufacturing most traditional constraints are removed, and you are left with nearly complete geometrical freedom. As such it is possible to build structures which mimic the human body structures & naturally occurring shells which has significantly increased strength per weight. Airbus APWORKS recently designed a new electric motorcycle with a topology-optimized hollow skeleton frame. The total weight of the motorcycle, which can be seen in figure 24, weighed in at $35kg$ with batteries and motor. Of these the frame was only $6kg$.

This new-found geometrical freedom is not only beneficial towards creating lightweight parts, it is also a necessary step to keeping the costs of additive manufacturing as low as possible due to current high prices on raw materials.

4.4.6 Assembly Simplification

NASA together with Stratasys Direct Manufacturing recently went through a redesign process of a fuel injector for one of their main rocket systems, where they utilized additive manufacturing to its potential. With the redesign of the injector, they reduced the assembly from over 150 parts down to two easily mountable parts, which was made possible with the internal geometry freedom that comes with AM. With the previous used manufacturing methods it could take a skilled craftsman multiple months to assemble each injector, whereas with the new method less than ten days total is required for production and assembly. As such this new process removed significant amounts of touch-labor leading to major savings.[48]

4.4.7 Material Utilization & Energy Savings

The additive manufacturing processes are generally seen as much more energy efficient compared to machining, however it isn't always the case since both the production of raw materials and the binding of these raw materials together are energy intensive processes. According to Airbus the technology reduces energy usage by up to 90%, significantly reducing the environmental footprint[49], however it is uncertain if this number includes energy savings from reduced fuel usage on their aeroplanes. It does however include the redesign of parts specifically for AM in order to reduce the materials usage and weight of parts.

With the very high Buy-to-fly Ratio found in aerospace parts, the switch towards additive manufacturing can make sense, by removing the need for recycling of large amounts of leftover materials and by significantly increasing fuel economy through weight reduction.

4.4.8 Reduced use of Hazardous Cutting Fluids

Cutting fluids are a type of lubricant and coolant fluid which is pushed at high pressures onto the work-piece during subtractive machining. This is done in order to cool the workpiece, and to lubricate the tooling as it cuts. The cutting action creates significant heat in the tool and workpiece which is transferred to the cutting fluid, in turn evaporating. Exposure to this vapor has been found to significantly increase likelihood of getting cancer in the esophagus, stomach, pancreas, colon, prostate, and rectum[50]. A CNC machine uses from a couple hundred liters to multiple tonnes of cutting fluid every year, and since the fluid is an emulsion of oil and water it has to be sent to a dangerous waste processing facility. The purchase and recycling of cutting fluid has been found by Hands et al. [50] to be between $7-17\%$ of total production costs.

With AM there are no cutting fluids being used for the production of parts, and as such the challenges associated with fluids are removed. This could increase worker happiness and reduce the overall worker absence. There is however an increased risk in working with the fine grained powders used in Powder bed fusion processes, which is currently under-investigated and not fully understood[51]. Some of the manufacturers of parts using AM have begun using full hazmat-suits in order to guarantee their workers safety, which seems like a reasonable measure.

4.4.9 Supply Chain Alteration

Additive manufacturing is currently not being applied in any scale which impacts the supply chains in which most manufacturing is achieved. The supply chain in this context consists of a product produced at a large scale factory in some low-cost country, which is transported via air, land, or water; to multiple locations, where it is sold to an end customer, through a retailer. Chen [52] argues that with increased maturity of additive technology it is reasonable to assume that production can be moved closer to the end customer. This should lead to significant cost savings from reduced freight and handling of cargo, as the transportation of raw material for additive manufacturing processes are very compact, and lend themselves better towards transportation than finished products. As such this should show a reduction in costs, or at least a transfer of earnings from transportation companies towards the manufacturer.

A complete changeover to additive manufacturing is however not reasonable to assume, and probably not beneficial to the end user, as even with a hundred times increase in additive efficiency it could still not rival the most efficient moulding processes, which are pumping out millions of parts per day. Most users of these moulding processes are however currently forced to hold on to the original mould tooling for many years, in order to satisfy consumers with spare parts. This takes up significant storage space and can be seen as somewhat wasteful use of resources, especially for non-critical parts. With AM these parts can be created without tooling, and produced to order by the end customer, directly by the original local retailer. This act of printing spare parts for appliances or vehicles etc, could however lead to Intellectual Property infringement which must be discussed with the OEM manufacturer.

4.5 Challenges Associated With Adoption of AM

The challenges in increasing adoption of AM can be seen as byproducts of the manufacturing processes that we are accustomed to using. Engineers that have "grown up" with the knowledge of traditional machining and casting processes, might have problems with breaking away from building parts of relatively low geometrical complexity. With additive manufacturing it is wise to consider designs which are significantly different compared to what would be createable through traditional methods, and most of the companies that provided additive manufacturing services had received designs which were clearly designed for manufacturability through other processes.

4.5.1 Limitations of Traditional CAD Software

With most of the traditional Computer-aided design (CAD) systems that exist today you get a solid modeling tool which bases its creation of 3d-models from two-dimensional sketches which can be "extruded" or "revolved". This process generally doesn't lead to very advanced shapes unless the designer puts a lot of time and effort into the creation of the geometry. Introduction of more advanced CAD systems with improved functionality towards creating parts optimized for additive manufacturing, should lead to increased adoption, as the current freeform surfacing and topology optimization tools can be quite daunting to work with unless you have training specific for them.

Further most CAD systems today are standalone applications with at best an add-on for programming CNC machines. This programming act can also be done through a second piece of individual software, which is called Computer-aided manufacturing (CAM). Control of additive manufacturing systems are usually done through a third, generally proprietary piece of software. In order to bring down the costs of not only additive manufacturing, but the complete manufacturing chain for small scale production, an integrated CAD software, with slicer functionality built in, combined with CAM features is proposed as a means of achieving much better in-shop effectiveness. This integrated software could introduce traceability throughout the manufacturing process; so that it proposes CNC finishing strategies directly from the as-produced additive model.

4.5.2 Cost of AM Systems Contribution to Parts Price

The costs of most additive systems have over the last ten years been significantly reduced. The machine costs themselves are however still a major part of the parts pricing, with machinery costs found between 130 000USD for EOS GmbHs simplest plastic SLS offerings, the formiga P110, and 800 000 USD for their P760. The mainstream FDM™ offering from Stratasys, the Fortus 450mc is found at 140 000USD.

Costs of metal additive systems are even higher with costs found between 300 000 USD (Ø100mm x95mm build volume, not large enough for any of the aluminium parts used in this thesis) and 1 400 000 USD (400x400x400 build volume) for the larger systems with increased build speed.

As all businesses seek to maximize profits, an absolute minimum would be that the machines themselves need to re-earn their own purchase costs. As such a minimum earning per day for these systems exist between 70 and 770USD, running 24 hours a day, non-stop, for five years continuously, without regards to materials, service costs, power consumption and administrative costs. From the numbers it is clear that the systems have a long way to go into becoming mainstream offerings, and probably that the companies which offer manufacturing services through AM are not achieving substantial earnings from their investments at this moment.

Lindemann et al. [53] found machine costs of over 70% when benchmarking an automotive stainless steel 316 part through additive manufacturing. In this thesis it would however prove impossible to calculate the machine costs for each quote, taking build speed, machine costs and overhead into account for each individual quote through different machinery.

With such large costs associated with them, and changes happening in the machine-offering of additive manufacturing systems on a near-yearly basis it is understandable that the owners of machine shops are hesitant to shell out up to a million USD in order to get their hands on a metal-printing AM Machine, when it also could be outdated in as little as five to eight years. With the enormous development seen on the forefront of technology it becomes hard to judge when the time is right for acquiring one of these systems. Should you acquire it too early it will be of limited use, and if you acquire it too late you'll be overrun by competitors with more knowledge on the field.

4.5.3 Cost of Materials / Lack of Material Standards

It has been found that many of the companies that make additive manufacturing machines are using the raw materials as a secondary business model, due to lack of standards for additive manufacturing materials. All of the machine producers are currently supplying materials for their machines, however some of them have opted to use locked control systems that only accept the manufacturers proprietary powders or filament. With each machine manufacturer trusting only their own materials for production, this leads to both increased price and pollution due to excessive shipping between the original powder/filament producer and the machine manufacturer which verifies the material. In contrast, for CNC machining all materials are delivered from a material-supplier, and the tool manufacturer recommends cutting parameters.

In order to increase the competitiveness of additive manufacturing methods it would be wise of machine manufacturers to go together, and verify that a certain standard of materials work for their machines at certain process parameters, rather than reselling verified materials at increased price. The original material producer should normally be considered at least as competent at verifying if the material is within specifications, as they have been producing these types of materials for decades.

Because high material costs are found to impact the final pricing of products, one of the interviewed companies went through extensive testing of materials from a third party materials manufacturer, at 50% reduced cost, without detrimental effects on quality. Based on this it is clear that a joint-industry project could significantly improve material costs by increasing production volumes of raw materials for the processes.

Further it can be seen that the high material costs of the proprietary material for the FDM™ process could be a hindrance towards its increased adoption when compared to Nylon sintering in PBF machinery, when this becomes more common knowledge.

5 Conclusion

Overall the additive manufacturing process has been found to be quite price competitive when compared to CNC machining of few parts, with the production of plastics leading the way.

5.1 Price performance of Additive Manufacturing of Plastic Parts

Both Powder Bed Fusion (PBF) & fused deposition modeling (FDM™) shows great promise for the production of small volumes of plastic end use products, when compared to the CNC machining techniques. It still cannot hold the best of tolerances nor does it give a perfect surface finish, but with regards to price it has been shown that it is a very competitive technology. At producing a one-off of part I it was found to be in average 75% cheaper than its CNC alternative, dropping down to 54% cheaper when producing 20 units. For part II it continues to outclass its CNC counterpart, with production through AM methods being less than one-tenth of the cost for the first unit, dropping down to one-fifth for twenty units. The lowest unit cost for CNC machining was found to be 39 USD in china, which is still 3 times as expensive as the lowest price found with AM, through the SLS process by a company in the Netherlands.

From part I, it is seen that FFF is between $50-70\%$ more expensive than its PBF counterpart, and for part II it is found to between $80-130\%$ more expensive. This can seem counter-intuitive when seen from a technical standpoint, as the PBF process should in theory use more of an operators time when compared to FFF, due to extra work with machine cleanup from raw powders. Material price for FDM™ is however over four times as expensive as the Nylon powder used for these parts with PBF, and was found to be around 19% of the average price per unit when producing 20 units through FDM™, versus 7% of the cost when using PBF.

It should however be noted that both the plastic parts which were evaluated in this work has been of relatively small size, and that the cost-effectiveness of the additive technology diminishes with increased size, due to higher material costs.

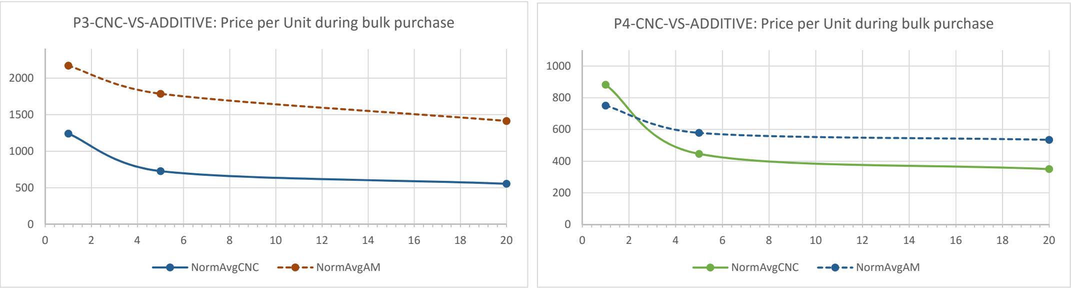


Figure 25: Average costs of CNC vs AM for the aluminium parts

5.2 Price Performance of Additive Manufacturing of Aluminium Parts

The price performance of additive manufacturing of metal parts has been found to be less competitive to CNC machining than its plastic counterpart. The method of using selective laser sintering/melting was found to be between 75 and 155% more expensive than CNC milling, when producing the larger of the two aluminium parts(Part III). However for the production of the smaller part it was found to be on par with CNC machining for the first couple of units, and then ended up being 52% more expensive when producing 20 units. As such it shows that the volume of material which is built is the most important parameter, as both material costs and build time depend directly upon it. For the production of aluminium parts through additive manufacturing, an average price of between 7.5 USD/cm^3 and 12 USD/cm^3 was found, of which large parts can be attributed to the cost of machinery.

5.3 Preferential steps towards increased adoption of AM

This work proves that the additive methods can be used as a good alternative to CNC machining of few items. As such to increase the adoption of AM it is important that we start showcasing how good the additive methods can be, and prove that they are cost-efficient compared to their alternatives. New CAD systems should offer better solutions to freeform modeling and optimalization for AM. Improved interaction between CAD, CAM and 3d printers should be proposed to software-makers in order to increase their usability. Further focus on reducing costs of machinery and materials for the methods can be seen upon as key enabling improvements towards a fruitful future with additive technology.

6 Further work

This thesis shows that additive manufacturing is starting to become adopted as a viable production method for both plastic and metal parts as end use products. As the metal additive manufacturing methods were found to not quite have reached its peak potential just yet, it could be interesting to re-evaluate its costs in a few years when it has gained further traction.

It could be especially interesting to verify the claims of significantly increased build speed set forth by Arcam AB (the producer of EBM machines), seen from a cost-perspective when producing either titanium or stainless steel parts; or once again for aluminium should they begin to offer that.

During the work on this thesis a new method of manufacturing parts has been officially launched into the market, with a technology named Continuous Liquid Interface Production (CLIP) which is closely related to Stereolithography. The company is named "Carbon", and their technology promises more than twenty-five times the production speed of any other additive method, whilst saying that their materials are engineering grade polymers which are not affected by UV-light. A bold claim one might say, but a verification study of their claims could be a good theme for further evaluation.

References

[1] CNC Zone. Image of 3-axis cnc mill. Online Resource. URL http://www.cnczone.com/forums/attachment.php?attachmentid=275744&d=1394656349&thumb=1. Accessed last 15.06.2016.

[2] Bobcadafterdark. Image of 4-axis cnc mill. Online Resource. URL http://bobcadafterdark.com/wp-content/uploads/2013/02/bobcad-cam-4-axis-cnc-programming-cad-cam-software.png. Accessed last 15.06.2016.

[3] Manufacturing Alliance Associates Inc. Image of 5-axis cnc mill. Online Resource. URL http://www.mfgaa.com/5axis.table.table.jpg. Accessed last 15.06.2016.

[4] Swiatdruku 3d. Image of fdm machine. Online Resource. URL http://www.swiatdruku3d.pl/wp-content/uploads/2013/03/FDM.png. Accessed last 15.06.2016.

[5] Paul Sieradzki. Image of infill structures. Online Resource. URL https://paulsieradzki.files.wordpress.com/2014/04/infill.png. Accessed last 15.06.2016.

[6] Materialgeeza. Image of stereolithography apparatus. Online Resource. URL https://en.wikipedia.org/wiki/Stereolithography#/media/File:Stereolithography_apparatus_vector.svg. Accessed last 15.06.2016.

[7] Additively. Image of binder jetting machine. Online Resource, . URL https://www.additively.com/img/content/learn/process/additive-manufacturing-binder-jetting-en@2x.png. Accessed last 15.06.2016.

[8] DMG Mori. Image of directed energy deposition. Online Resource. URL http://us.dmgmori.com/blob/350798/1b7304794e66bd646af5acbd219b801e/5-intermold-lasertec-data.jpg. Accessed last 15.06.2016.

[9] Slideshare. Image of the sintering process. Online Resource. URL http://image.slidesharecdn.com/class16-141101044946-conversion-gate01/95/class16-14-638.jpg?cb=1414817408. Accessed last 15.06.2016.

[10] Additively. Image of selective laser melting. Online Resource, . URL https://www.additively.com/img/content/learn/process/additive-manufacturing-laser-melting-en@2x.png. Accessed last 15.06.2016.

[11] Cod Toy. Image of topologic map by sheet lamination. Online Resource. URL https://s-media-cache-ak0.pinimg.com/736x/c8/5b/3e/c85b3e77d7f613b2f81b0d79e8f4bdff.jpg. Accessed last 15.06.2016.

[12] John W Gillespie. Image of ultrasonic consolidation. Online Resource. URL https://www.researchgate.net/profile/John_Gillespie_Jr/publication/233958195/figure/fig2/AS:281606943199249@1444151735289/Figure-1-Schematic-of-the-ultrasonic-consolidation-process.png. Accessed last 15.06.2016.

[13] 3D Systems. Adopted images from youtube video. Online Resource. URL https://www.youtube.com/watch?v=r-p7BBuci1w&list=PLV-P03qVWLPb7KzhNDD7quxQPD5ZG2wNb. Accessed last 15.06.2016.

[14] Sculpteo. Image of fff quality. Online Resource, . URL https://www.sculpteo.com/media/imagecontent/FDM%20TOP.jpg. Accessed last 15.06.2016.

[15] Sculpteo. Image of sls quality. Online Resource, . URL https://www.sculpteo.com/media/imagecontent/SLS%20TOP.jpg. Accessed last 15.06.2016.

[16] ION Racing 2016. Engineering drawing of part 3, .

[17] ION Racing 2016. Engineering drawing of part 4, .

[18] Airbus APWORKS. Image of airbus apworks light rider motorcycle. Online Resource. URL `http://www.3dprintingbusiness.directory/wp-content/uploads/2016/05/light-rieder-3D-printed-e-bike-by-APworks.jpg`. Accessed last 15.06.2016.

[19] C.W. Hull. Apparatus for production of three-dimensional objects by stereolithography, March 11 1986. URL `http://www.google.com/patents/US4575330`. US Patent 4,575,330.

[20] K Schischke, E Hohwieler, R Feitscher, J König, S Kreuschner, P Wilpert, and N Nissen. Energy-using product group analysis - lot 5 machine tools and related machinery task 2 report – economic and market analysis. 2009. URL `http://www.ecomachinetools.eu/typo/reports.html?file=tl_files/pdf/EuP_Lot5_Task2_August2012_FINAL.pdf`.

[21] American Society of the International Association for Testing and Materials. Standard terminology for additive manufacturing technologies. Online resource. URL `http://www.astm.org/FULL_TEXT/F2792/HTML/F2792.htm`.

[22] Dr. Ian Gibson, Dr. Brent Stucker, and Dr. David W. Rosen. Additive manufacturing technologies - rapid prototyping to direct digital manufacturing. Online resource, 2010. URL `http://link.springer.com/book/10.1007%2F978-1-4419-1120-9`.

[23] Wohler associates. Wohlers report 2015. Online resource, Yearly business report, 2016.

[24] Greg Morris. Additive manufacturing at ge. Online resource, 2014. URL `http://www.gecapital.com/webinar-assets/pdf/3dprinting-capital.pdf`.

[25] PriceWaterhouseCooper & Manufacturing Institute. 3d printing and the new shape of industrial manufacturing. Online resource, 2014. URL `http://www.themanufacturinginstitute.org/~/media/2D80B8EDCCB648BCB4B53BBAB26BED4B/3D_Printing.pdf`.

[26] CFM Aero. Leap - the power of the future. Online resource, 2015. URL `http://www.cfmaeroengines.com/files/brochures/LEAP-Brochure-2014.pdf`.

[27] Mitjan Kalin and Janez Kogovšek. Surface roughness and its effects in tribology. In *1st BioTiNet Workshop, in Ljubljana, Slovenia*, 2011.

[28] Concept Laser. Laser melting metal systems, 3d printing metal for aerospace industry. Online resource, 2016. URL `http://www.concept-laser.de/en/industry/aerospace/machines.html`. Last accessed: 27.05.2016.

[29] Paolo Minetola, Luca Iuliano, and Giovanni Marchiandi. Benchmarking of fdm machines through part quality using it grades. *Procedia CIRP*, 41:1027–1032, 2016.

[30] Jean-Pierre Kruth, Peter Mercelis, J Van Vaerenbergh, Ludo Froyen, and Marleen Rombouts. Binding mechanisms in selective laser sintering and selective laser melting. *Rapid Prototyping Journal*, 11(1):26–36, 2005. URL `http://dx.doi.org/10.1108/13552540510573365`.

[31] Steeltank. Relative pricing of alloys. Online resource, 2012. URL `http://www.steeltank.com/Portals/0/Pressure%20Vessels/SSWseminarOct2012/Relative%20Cost%204%2015%202012.pdf`.

[32] Murray Jacobson, Austin R Cooper, and John Nagy. Explosibility of metal powders. Technical report, DTIC Document, 1964.

[33] Jason Dawes, Robert Bowerman, and Ross Trepleton. Introduction to the additive manufacturing powder metallurgy supply chain. *Johnson Matthey Technology Review*, 59(3):243–256, 2015. URL http://www.technology.matthey.com/pdf/243-256-pmr-jul15.pdf.

[34] Neil Hopkinson and P Dicknes. Analysis of rapid manufacturing—using layer manufacturing processes for production. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 217(1):31–39, 2003.

[35] M Ruffo, Chris Tuck, and R Hague. Cost estimation for rapid manufacturing-laser sintering production for low to medium volumes. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 220(9):1417–1427, 2006.

[36] Charles Schell. The value of the case study as a research strategy. *Manchester Business School*, 2, 1992.

[37] Stratasys. Design guidelines: Direct metal laser sintering. Online resource, . URL https://www.stratasysdirect.com/resources/direct-metal-laser-sintering-dmls/. Last accessed: 27.05.2016.

[38] Jagdish N Bhagwati. Why are services cheaper in the poor countries? *The Economic Journal*, 94(374):279–286, 1984.

[39] The World Bank. Gdp per capita, ppp (current international $). Online Resource, 2014. URL http://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD?order=wbapi_data_value_2014+wbapi_data_value+wbapi_data_value-last&sort=desc. Accessed last 11.06.2016.

[40] Ville Matilainen et al. Benchmarking of laser additive manufacturing process. 2012. URL http://www.doria.fi/bitstream/handle/10024/84863/BSc%20Thesis%20Matilainen%20fv.pdf?sequence=1.

[41] Stratasys Inc Jesse Hanssen. Fdm 400mc accuracy assessment. Online resource, 2008. URL http://www.trosol.com/fortus/downloads/FDM400mc_Accuracy.pdf.

[42] Stratasys. Fortus 380mc and 450mc 3d printer systems. Online resource, . URL http://www.stratasys.com/3d-printers/production-series/fortus-380-450mc.

[43] Mohamed Mohamed Zabti. *Effects of light absorber on micro stereolithography parts*. PhD thesis, University of Birmingham, 2012.

[44] 6082-t6 aluminum. Online resource. URL http://www.makeitfrom.com/material-properties/6082-T6-Aluminum.

[45] David Sedwick. Just-in-time dedicated seat plants fall out of favor. 2010. URL http://www.autonews.com/article/20100803/OEM01/100809975/just-in-time-dedicated-seat-plants-fall-out-of-favor. Original article author is David Sedwick, but he directly quotes Richard Morris, vice president assembly at BMW Spartanburg. Last accessed 11.06.2016.

[46] Jianxin Jiao, Qinhai Ma, and Mitchell M Tseng. Towards high value-added products and services: mass customization and beyond. *Technovation*, 23(10):809–821, 2003.

[47] Martin Masters, Therese Velde, and Fred McBagonluri. Rapid manufacturing in the hearing industry. *Rapid manufacturing: an industrial revolution for the digital age*, pages 195–209, 2006.

[48] Stratasys. Nasa marshall space flight center turns to 3d metal printing for sls propulsion program. Online resource, . URL https://www.stratasysdirect.com/case-studies/nasa-sls-propulsion-program/. Last accessed: 13.06.2016.

[49] Peter Sander Airbus. Fast - flight airworthyness support technology vol 55. Online resource, 2015. URL http://www.airbus.com/support/publications/?eID=maglisting_push&tx_maglisting_pi1%5BdocID%5D=41107.

[50] David Hands, Maura J Sheehan, Ben Wong, and Henry B Lick. Comparison of metal-working fluid mist exposures from machining with different levels of machine enclosure. *American Industrial Hygiene Association Journal*, 57(12):1173–1178, 1996.

[51] JM Benson. Safety considerations when handling metal powders. *Journal of the Southern African Institute of Mining and Metallurgy*, 112:563–575, 2012.

[52] Zhen Chen. Research on the impact of 3d printing on the international supply chain. *Advances in Materials Science and Engineering*, 2016, 2016.

[53] Christian Lindemann, Ulrich Jahnke, Matthias Moi, and Rainer Koch. Analyzing product lifecycle costs for a better understanding of cost drivers in additive manufacturing. In *23th Annual International Solid Freeform Fabrication Symposium–An Additive Manufacturing Conference. Austin Texas USA 6th-8th August*, 2012.

Appendix

Interviewee list (Name, Title, Company)

- Anders Reve, Sales manager, Simplify AS
- Alf Inge Haland, Key account manager, Aarbakke AS
- Eivin Strømland, Sales & Marketing Manager, Promet AS
- Jonas Mersch, Product Management, SLM Solutions GmbH
- Pär Jansson, Area Sales Manager Nordic & Baltic, EOS Nordic AB

Currency data

All calculations regarding currency have been calculated with the following exchange price taken from the Google currency database;

30.05.2016 15:59

- GBPNOK 12,2082937
- EURNOK 9,2980347
- USDNOK 8,34877857
- NOKUSD 0,119778
- EURUSD 1,1137
- GBPUSD 1,462285

(https://www.google.com/finance/converter)

Price quotes & CAD Data

In the interest of protecting the competitive advantages of the respective manufacturing companies which are operating in direct competition between eachother, the datasets acquired throughout this work will not be included, as the inclusion of such documentation could lead to revealing a companies pricing strategy.

All the needed CAD documentation for reproducing your own similar results are included in the attachment zip file. This information includes Autodesk inventor part files, STL files, STP files and pdf engineering drawings of all the parts.

Questions from which the interview guides were created

How does your company look on the future of additive manufacturing for smaller production volumes?

How does your company work towards implementing new technology, and keeping up to date with the newest trends in manufacturing?

What are your thought on additive manufacturing technology, and how do you see it affecting your business?

Which barriers exist towards increased adoption of Additive manufacturing methods?

Which existing challenges do you have with manufacturing methods of today, and how would you like to see them evolve?

What type and manufacturers of additive manufacturing systems does your company use?

What type of parts are your company receiving orders on producing through additive methods?

Is all of your work primarily with certain alloys?

How much work can be estimated in changing from one material to another in the same machine?

Does your company work together with other manufacturers of powder bed fusion machines in order to make use of common powders?

I saw your company has their own material *******, is this a material that has been developed at your company individually or through cooperation with other companies and vendors?

Are the powders that your machines use, the same as the powders used in general powder metallurgical processes such as sintering of brakepads under pressure? If not, could you explain the differences?

Why did you choose the type of machinery that you did? Please explain your thoughts, if there were any at that time.

What kind of deposition rates are you achieving in your processes?

Do you have any estimates regarding time use of a one-off job versus one that fills the machine in XY-direction (Nesting of parts in 2d).

How does your machines differ from other powder bed fusion machines utilizing selective laser sintering with full melting of metals (Non solid-state sintering)?

Can powders from alternative manufacturers be used in your machines or does ***** supply their own verified materials from selected manufacturers?

Does your company work together with other manufacturers of powder bed fusion machines in order to make use of common powders in order to increase production volumes?

And are the powders the same as the powders used in general powder metallurgical processes such as sintering of brakepads under pressure?

What are the costs of a new ******* system (I know it is an exact number based on installation etc, but rough figures are okay here. Are we talking 250,000 usd/eur or 1million+ usd/eur?)

How much does a kilogram/certain volume of AlSi10Mg / Inconel 718 / Ti6Al4v cost in purchase (And what final density can be used to calculate volumetrics? 95% dense or closer to 100%?)

Does your systems require a certain mix of "virgin" to used powders?

How much work can be estimated in changing from one material to another in the same machine?

What are the associated costs of your machines and the extra costs introduced through using these machines?

What are the costs of powders that are available for your machines, specifically the PA12/PA2200 and AlSi10Mg?

How does pricing of materials affect final price of parts, and what are you doing to decrease material costs?

Does your company work together with other manufacturers of powder bed fusion machines in order to make use of common powders?

Which new features would you like to see in traditional CNC machines? And which software changes could be done to improve your effectiveness?