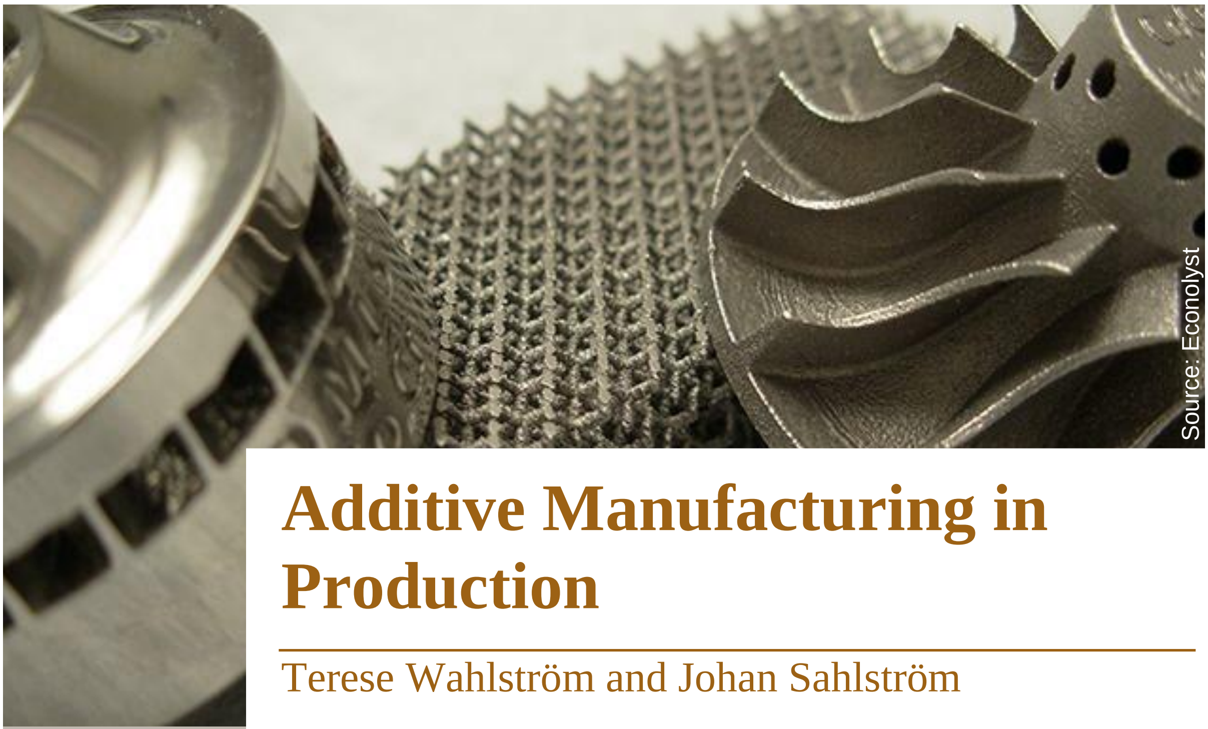


Additive Manufacturing in Production

Terese Wahlström and Johan Sahlström

DIVISION OF PRODUCT DEVELOPMENT | DEPARTMENT OF DESIGN SCIENCES
FACULTY OF ENGINEERING LTH | LUND UNIVERSITY

2016

MASTER THESIS

Additive Manufacturing in Production

For the Automotive Industry

Terese Wahlström and Johan Sahlström

LUND UNIVERSITY

Additive Manufacturing in Production
For the Automotive Industry

Published by
Department of Design Sciences
Faculty of Engineering LTH, Lund University
P.O. Box 118, SE-221 00 Lund, Sweden

Subject: Machine Design for Engineers (MMK820), Technical Design (MMK920)
Division: Product Development
Supervisor: Olaf Diegel
Co-supervisors: Torbjörn Larsson, Babak Kianian, Damien Motte
Examiner: Giorgos Nikoleris

Abstract

In the past two years the development and the adoption of additive manufacturing, colloquially named 3D printing, seems to have increased considerably, so much that it is difficult to keep up with all the advancements. Meanwhile, from a competitive perspective it is necessary to holistically keep investigating when additive manufacturing is appropriate for the automotive industry and to also build on the already known.

This thesis attempts to create a good base for documenting the already known and the future work. Firstly, the seven categories of machine processes are shortly presented for a basic understanding on the possible outcome, in material properties, sustainability and cost. Then a benchmark on how others are using the technology today was carried out to discover applications and also to speculate on which areas the technology are mature enough. In parallel to this, a literature study was done in which a theoretical perspective on how additive manufacturing can contribute to increased customer value is presented. Together, these three chapters might help readers discover new applications. Beyond the maturity of the technology it is also necessary to evaluate how it might affect the work at research and development (R&D) as it also might affect the business case. All of these areas build up with information on how and when additive manufacturing can be wisely implemented in production.

To decrease knowledge gaps, three case studies were carried out. A component was developed using the geometric advantages of additive manufacturing in direct part manufacturing, in this case it involved part consolidation while also decreasing the weight. It was topology optimised for aluminium, steel and titanium. Tests on plastic components were also carried out, both on the ease of post processing of a complex part and destructive tests on several combinations of materials and machines.

Keywords: additive manufacturing, 3D printing, automotive, application areas, production

Sammanfattning

Under de senaste två åren har utvecklingen inom additiv tillverkning, i vardagligt tal benämnt 3D printning, och dess tillämpningar ökat så markant att det börjar bli svårt att hålla sig uppdaterad om utvecklingen. Samtidigt så är det ur ett konkurrensperspektiv nödvändigt att holistiskt fortsätta utreda i vilka fall additiv tillverkning är lämpligt för fordonsindustrin och bygga upp en kunskapsbas.

Detta arbetet försöker skapa en bra grund för dokumentering av den redan befintliga kunskapen och framtida arbete. I den första delen av arbetet presenteras de sju process kategorierna kort för en grundförståelse i vad som är möjligt i materialegenskaper, hållbarhet och kostnad. Därefter utreddes vad andra använder teknologin till, dels för att upptäcka användningsområden och dels för att spekulera i vad tekniken är mogen för. Parallellt med detta så undersöktes applikationerna från ett mer teoretiskt perspektiv i hur additiv tillverkning kan bidra till ett ökat kundvärde. Tillsammans kan dessa tre kapitel kanske hjälpa läsaren att komma på nya användningsområden. Utöver teknikens mognadsgrad så är det också viktigt utvärdera om hur additiv tillverkning kan påverka arbetet på research and development (R&D) eftersom även detta kan påverka business case. Alla dessa områden bidrar till kunskap om när teknologin kan användas smart i produktion.

För att minska på vissa kunskapsluckor inom dessa områden så utfördes fallstudier. En komponent utvecklades särskilt designad för att utnyttja fördelarna additiv tillverkning kan ge vid direkttillverkning av slutprodukt. I det här fallet kunde några detaljer integreras samt vikten reduceras. Komponenten var topologioptimerad för aluminium, stål och titan. Dessutom genomfördes studier på flertalet olika kombinationer av material/maskin för plastdetaljer, både ett test på efterbearbetning av en komplex detalj och hållfasthetstester.

Nyckelord: additiv tillverkning, 3D printning, bilindustri, användningsområden, produktion

Preface

This paper presents the final project of our master degrees in product development and industrial design within the Mechanical Engineering programme at Lund University. It is a collaboration between the division of Product Development at Lund University and R&D at Volvo Car Group in Gothenburg.

We especially want to thank our supervisor at Volvo Car Group, Torbjörn Larsson, for his tireless support and vast knowledge within the automotive industry. Many more at Volvo Car Group have helped us during our project, Harald Hasselblad and Marcel Kapocs to name a few.

From Lund University we would like to thank our main supervisor Olaf Diegel and, our assistant supervisors Babak Kianian and Damien Motte for their support and expertise knowledge in additive manufacturing and product development.

It has been a very insightful journey, getting to know all the perks and pitfalls of additive manufacturing. Though the more information we obtained on the subject, the more we knew we did not know.

Lund, January 2016

Terese Wahlström and Johan Sahlström

Table of Contents

List of Acronyms and Abbreviations 10

1 Introduction 11

1.1 Volvo Car Group 11

1.2 Problem Identification 12

1.3 Deliverables and Delimitations 15

1.4 Research Methodology 15

1.4.1 Case Studies 17

1.4.2 Interviews 17

1.4.3 Literature Review 17

1.4.4 Questionnaires 18

1.5 Report Outline 18

2 Seven AM Process Categories 20

2.1 Introduction 20

2.1.1 AM Materials 21

2.1.2 Sustainability 21

2.1.3 AM Cost Breakdown 22

2.2 Binder Jetting 24

2.3 Directed Energy Deposition 26

2.4 Material Extrusion 28

2.5 Material Jetting 30

2.6 Powder Bed Fusion 32

2.7 Sheet Lamination 35

2.8 Vat Photopolymerization 37

2.9 Future Work 40

3 Benchmark 41

3.1 Introduction 41
3.2 Automotive 42
3.2.1 Passenger Cars 42
3.2.2 Motorsport 55
3.3 Aerospace 57
3.3.1 Airbus 58
3.3.2 European Space Agency, ESA 60
3.3.3 General Electric, GE 61
3.3.4 Rolls Royce 62
3.4 Tooling 62
3.4.1 Injection Moulding 62
3.4.2 Thermoforming 64
3.5 Lessons Learned 65
3.6 Future Work 65
4 Application Areas 66
4.1 Introduction 66
4.1.1 Value Theory 66
4.1.2 Some AM Enablers and Barriers 67
4.2 AM in Modelling and Prototyping 68
4.3 AM in Tools, Tooling and End Products 70
4.3.1 End Products with Conventional Design 72
4.3.2 End Products with AM Design Advantage 72
4.3.3 Manufacturing Aids 74
4.4 AM in Services 74
4.5 Some Specific Areas 75
4.5.1 Minimising Environmental Impact 75
4.5.2 Designed Around You 75
4.5.3 Opportunities in Logistics 76
4.6 Future Work 76
5 Design Methodology 77

5.1 Introduction 77
5.2 Data Processing 79
5.3 Future Work 81
6 Case Studies 82
6.1 Tests on Plastic AM Components 82
6.1.1 Ease of Post Processing Test 82
6.1.2 Destructive Tests 84
6.1.3 Questionnaire 96
6.2 Development of a Metal AM Component 97
6.2.1 Part Specification 98
6.2.2 Concepts and Concept Selection 98
6.2.3 Concept Refinement 99
6.2.4 Thoughts on Product Verification and Validation 102
6.2.5 Lessons Learned 103
7 Implementation of AM 104
7.1 Introduction 104
7.1.1 Motivation 105
7.1.2 AM Strategy Factors 106
7.2 Phases of Implementation 108
7.3 When to Implement AM in Production 109
7.3.1 AM Strategy Factors 110
7.3.2 Prioritising Projects 110
7.4 Future Work 111
8 Thesis Contribution 113
References 116
Appendix A Collected Data 125
A.1 Test on Plastic AM Components 125
A.1.1 Destructive Testing 126

List of Acronyms and Abbreviations

AM	additive manufacturing
BJ	binder jetting
CAD	computer aided design
CFRP	carbon fibre reinforced plastic
CLIP	continuous liquid interface production
DMLS	direct metal laser sintering
DMP	direct metal printing
DMS	direct metal sintering
EBM	electron beam melting
e.g.	for example
FDM	fused deposition moulding
i.e.	that is
LOM	laminated object manufacturing
N/A	not applicable, no answer or not available
NDA	non-disclosure agreement
QTY	quantity
R&D	research and development
RM	rapid manufacturing, when AM is used for end products
RP	rapid prototyping, when AM is used for prototyping
RT	rapid tooling, when AM is used for tools or tooling
SLA	stereolithography apparatus
SLM	selective laser melting
SLS	selective laser sintering
UTS	ultimate tensile strength
VCG	Volvo Car Group, also called Volvo Cars

1 Introduction

This chapter introduces the context and scope of the thesis.

1.1 Volvo Car Group

In the Swedish town of Gothenburg, Volvo Cars (short for Volvo Car Group, VCG) has been delivering automobiles ever since it was founded in 1927. The competitors at the time were often seen as unfit for the rough Swedish winter roads as they not seldom broke down – meaning that market shares could be captured with reliable vehicles. Combined with engineering ingenuity and access to premium local steel this enabled Volvo Cars' success. [1].

The founders declared early on their intent for a human-centric approach to design, with safety at heart [1].

> *"Cars are driven by people. The guiding principle behind everything we make at Volvo, therefore, is and must remain, safety."* – The founders Assar Gabrielsson and Gustav Larson in 1927 [1].

Building on this rich heritage a new design strategy was announced in 2011, named "designed around you", which still focuses on the human aspects whilst also aiming for a luxury experience [2]. The human-centric approach even seems to permeate throughout the enterprise in the care for the "individual, society and nature". This admirable emphasis on safety, quality and the human being are still as relevant for Volvo Cars today with their mission "to make people's lives easier, safer and better". [3].

Volvo Cars was one of the earliest adopters in additive manufacturing, dating as far back as 1988. Since then, Volvo Cars has closely followed the advancements in AM, invested in machines and on a few occasions even been involved in the development of machines. As always seeking human-centric and sustainable potentials when compared to its alternative. Using AM should not just be for the sake of it. [4].

1.2 Problem Identification

Additive manufacturing (AM) is defined by ASTM F42 and ISO TC 261 as "a process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" [5]. See figure 1.1. In every day conversation AM is often referred to as 3D printing. There is a long list of machines under the AM umbrella which needs to be treated separately as they are appropriate for different tasks.

AM provides a design freedom that is unmatched by other manufacturing methods, without the need of expensive tooling or developing thereof. This opens up for numerous opportunities such as testing ideas at low cost, minimising weight, manufacturing of complex geometries that previously would have been impossible, mass customisation, etc.

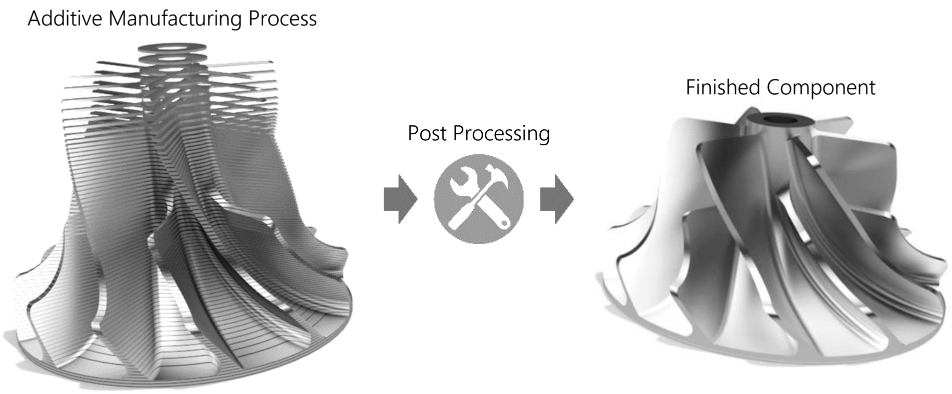


Figure 1.1 In additive manufacturing, material is joined together to form an object, enabling complex objects to be produced. This is usually done layer by layer and some post processing is usually required. [5].

There are barriers though for some usages of the technology such as low speed, high cost of materials and machines, need of post processing, and or lack of quality [6, p. 97]. Some predicts that in a few years at least some of these barriers will be reduced. Machines and material are expected to get less expensive and speed is expected to increase in the near future.[1] If these barriers are lowered it would result in making the technology more affordable, hence suitable for further applications.

[1] Between 2013 and 2018, Siemens predicts that the machines could get 400% quicker and 48% cheaper. Similarly, between 2018 and 2023 they predict additional 400% increase in speed and that it will be 31% less expensive. [7].

CLIP, a new AM technology that was introduced in the beginning of 2015, is said to be 25-100% quicker depending on the geometry of the object to be printed. Also verified by BMW. [8; 9].

Regardless of the AM barriers, the technology is currently being used for producing prototypes, tooling and even end use components directly for commercial use. Which suggests that there are economic viability in using the technology towards production in these specific applications today.

While some believe that AM technology will be the cause of the next industrial revolution and that it will replace all other manufacturing technologies, others believe it is a hype that is not appropriate for anything else than prototyping. A more realistic view would be that it depends on the usage, type of machine, material, etc. The quality of the print has to be acceptable for the specific use and the value of the product enhancements needs to outweigh the costs without compromising with neither environment nor safety.[2]

Looking beyond the hype, the research firm Gartner produces so called hype cycles. These are designed to illustrate where an emerging technology is at in maturity and adoption within companies, and possibly discover new opportunities without getting deceived by the hype. The strategic plan for a company contemplating adopting the technology will dictate to some extent when in relation to the placing on the cycle it is appropriate to invest. [10]. As seen in the figure 1.2, many of the relevant areas related to AM will reach the so called plateau of productivity within ten years, by then the technology is expected to be widely adopted within companies. [11].

To implement a new technology industrially within a company take time and if it will be used, for end products especially, many aspects need to be scrutinized. According to figure 1.2, the plateau of productivity for industrial AM will be reached within 5-10 years. And because of this tight time frame, there is a need to not only attack one problem at a time but several.

> *"The key is for a company to understand where and how to adopt AM to achieve increased business profit"* – Phil Reeves [12].

Understanding when the technology is suitable is important for a successful adoption. This means knowing both what the technology is suitable for and what a company is ready for or can be ready for within a certain time frame. The purpose of this thesis is therefore,

> *Investigate when AM is suitable for production in the automotive industry.*
> – Purpose of this thesis

[2] Volvo Car Group's core values are "*safety, quality and care for the environment*" [3].

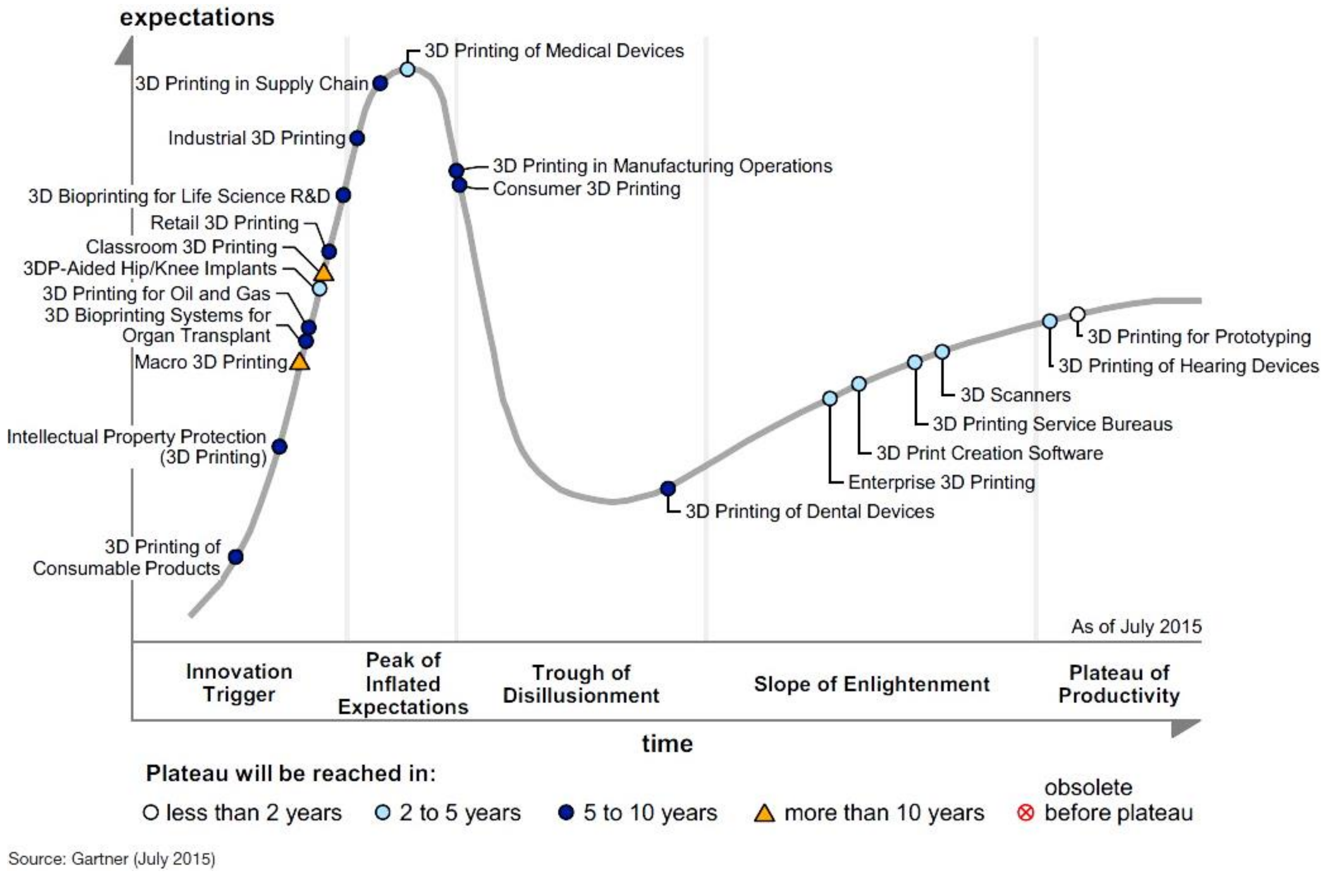


Figure 1.2 Hype cycle for additive manufacturing, in the graph referred to as 3D printing [13].

1.3 Deliverables and Delimitations

The scope of this work could be much larger than that of a master thesis. In an attempt to narrow the work, the following goal was formulated.

> *Present conclusions that aid in defining when AM is suitable for production in the automotive industry today and in the near future in a context that could easily be built upon.* – Goal of this thesis.

Exploring this further some steps in reaching the goal was defined, see figure 1.3. The work will have to briefly cover some of the areas to be able to get the bigger picture as the areas covered are quite extensive by themselves. The delimitations within these categories will be treated for each of the coming chapters. Other areas that could have been treated in separate chapters are "production planning and quality control" as they also will change with AM [14, p. 197].

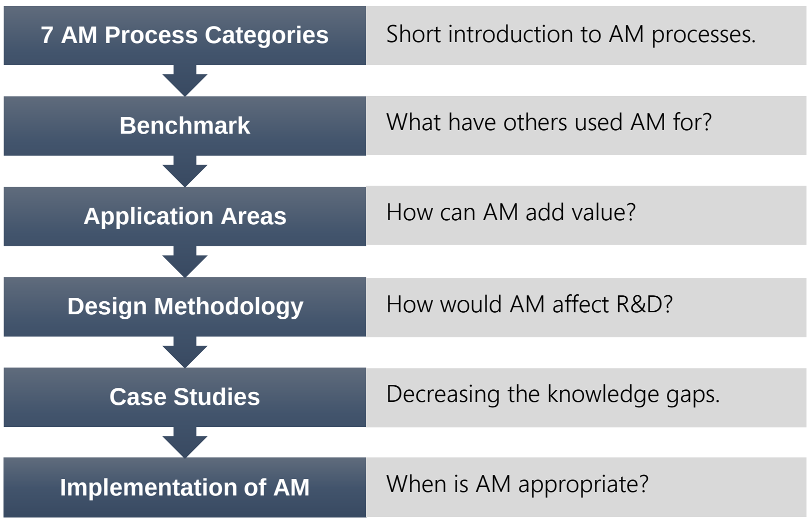


Figure 1.3 The areas of this work leading up to the conclusion.

1.4 Research Methodology

A good research methodology makes a project obtainable at the same time as it could maximise ones performance. The choice of method should therefore depend on the specific project's nature.

One distinction in research is whether it is primary or secondary. That is if the result is based on own original research, such as questionnaires and case studies, or if it is derived from others' primary work found in books, journals, etc. Combining several methods of collecting data could result in more accurate and refined conclusions, avoiding biased data. It is important however that regardless of the origin evaluate how applicable each information is and how it may be used correctly. [15].

To structure findings in the case studies and benchmark, table 1.1 was developed.

Table 1.1 Lessons learned explained. For each of the areas it should be evaluated, in which way the information can be used and if it is it necessary to do further research on the area.

	Lessons learned
7 AM categories	Does the study provide any knowledge on the various processes and machines and what these may be used for?
Application areas	Are any new application areas for VCG discovered in the study? Which? Any findings on how AM can enhance the feeling of increased human centric design?
Design methodology	Does the study in any way tell what a good or bad design methodology is? Does it provide knowledge in the tools needed for development? Will it depend on the application area? Does it fit with VCG's current methodology or does it need to change somehow for some applications?
Implementation of AM	In which way does the findings affect when AM is appropriate for implementation in production for VCG? Does it provide information on what VCG should prioritise?

According to [16] the position of the technology on the Gartner's hype cycle indicates what kind of research is relevant and feasible, see table 1.2. The areas that are relevant for automotive purpose is wide spread across the graph seen in figure 1.2. If a study would focus on all these areas then it would not be possible to achieve the same level of result. Furthermore, as the technology develops, it might be pushed either forward or backward on the curve, affecting the needed research.

In the early stages of the Gartner's hype cycle it is more probable that the data is biased as the available information at that time are limited. It is not until the phase slope of enlightenment that there might be enough information for unbiased research. [16].

Table 1.2 Feasible research per phase in the Gartner's hype cycle, adapted from [16, p. 247].

Phase of the technology	***Research***
Technology trigger	– Prototypes of the technology – Hardware
Peak of inflated expectations	– Case studies – Analysing cases gone wrong / right
Trough of disillusionment	
Slope of enlightenment	– Empirical financial-based – Organisational
Plateau of productivity	

This thesis is based on both primary and secondary research, and some parts could not be counted as research at all but rather gathering information from various sources to build up a good base – and as information is collected from several sources there are less risk of biased data. The methodologies in this thesis are described below.

1.4.1 Case Studies

It is first in the phase peak of inflated expectations that case studies become relevant if you are not part of the development of course, see figure 1.2. Prior to this the maturity of the technology is often too low. And after the phase trough of disillusionment, the use of case studies are less relevant as the technology and its implications after that stage are already well known. At these phases the available information is limited and therefore there is a risk that the published research are biased. [16]. Context-based studies, such as case studies, can form a solid foundation for the knowledge in one field if many studies have been conducted. [11].

To reach the goal of this thesis, numerous case studies could have been carried out, three separate studies were conducted.

- Test on plastic AM components printed in various materials and machines.
  - Ease of painting a complex component.
  - Destructive testing of impact and tensile test specimens.
- Development of a concept component for direct part production with metal AM.

The result from these case studies could provide information on how and when to implement AM in production. To be able to implement AM successfully though and to answer when AM should be used in-depth, more case studies will be needed than these three.

1.4.2 Interviews

The interviews of this paper was mainly used exploratory, finding out on some of the implications of the technology and best practices that might be difficult to come by in literature. These are not presented further in this thesis.

1.4.3 Literature Review

The literature review helped in defining the work by finding out what have been done already and in which way this thesis could contribute with original content. Hopefully, the info from the literature review provides the reader with a broad view on additive manufacturing which might easily be revised and built upon.

The literature review was conducted in both web based and physical libraries, by information available internally at VCG and by browsing the internet. The web based libraries was the main source of information, including but not limited to Elsevier, SAGE Journals, ScienceDirect and Springer Journals.

As the chapters leading up to the conclusion are very different in character, the findings in literature are presented within the relevant chapter, sometimes together with primary research. All the relevant theory could have been placed in one chapter instead but the flow of the thesis and ease of reading would have suffered.

1.4.4 Questionnaires

Questionnaires was sent out to the machine suppliers for the plastic components. Another questionnaire was intended to be sent to the chosen service bureau and machine manufacturer for the printing of the developed metal component though was never sent as the component never was printed in metal AM. The questions and answers will not be presented in the thesis, they are however described in chapter 6.

As with the interviews, the questionnaires of this paper was mainly exploratory. To find out some of the implications of the technology and best practices that might be difficult to come by in literature.

1.5 Report Outline

Chapter 1. Introduction

Introduces the work of the thesis, in which context it was written, why the study is needed and how it was conducted.

Chapter 2. Seven AM Process Categories

Shortly introduces the different types of processes of AM machines.

Chapter 3. Benchmark

Provides benchmark material in tooling and end products to date. This chapter provides knowledge to all of the other chapters also. Presents some examples on how the technology might add value and often biased examples on maturity.

Chapter 4. Application Areas

Investigates how AM adds value and attempts to categorise applications.

Chapter 5. Design Methodology

Shortly introduces design methodology linked to AM.

Chapter 6. Case Studies

Presents the case studies in this thesis. This chapter provides knowledge to all of the other chapters also. It is presented separately for easy reading on some of the original content for the thesis.

Chapter 7. Implementation of AM

Introduces theory on the implementation of AM and presents conclusions on when AM could be implemented wisely.

Chapter 8. Thesis Contribution

Presents who have contributed with which parts of the thesis and what the thesis has contributed with.

2 Seven AM Process Categories

The ASTM F42 and ISO TC 261 defines seven distinctly different categories of AM processes. It is important to separate as the possible outcome are dependent on which process is used and even on the specific machine.

2.1 Introduction

One frequent question regarding AM is the maturity of the technology, is it really useful for my needs? As you will see in the benchmark in chapter 3, it is possible quality wise to use in some applications even for tooling and for end products. However, there are more to maturity than quality – sustainability and economics for example should also be included. For some uses though, the AM technology might never be mature enough relatively to other manufacturing.

> *"Just because a part can be produced using AM does not necessarily mean that it should be."* [17, p. 178].

A project should always be compared to its alternative, if the AM solution is more cost effective or if it could add value in some other way (e.g. decreasing lead-time or the environmental impact) it could be worth considering AM. See chapter 4.

It is essential to know the basics of the AM machines to understand what outcome is possible and which process to use. The resulting material properties, available materials, sustainability, economics, etc. are all intricately linked to the process of the specific machine. A discussion on these topics is therefore best done within each of the AM process categories, though there are not information publically available on many of these processes to make a thorough study. Instead, these topics are discussed briefly and the seven AM process categories are described separately.

- binder jetting
- directed energy deposition
- material extrusion
- material jetting
- powder bed fusion
- sheet lamination
- vat photopolymerization

2.1.1 AM Materials

The very basic principle of material characteristics and tolerances in AM is that it originates from the base material and the way the part is built. As you will see later in this chapter, AM is quite diverse at both ends. The way each layer could be adhered to the previous could be either thermally or chemically, and could be done a whole cross section at once or point wise be scanned over a cross section. And the base material could be anything from liquid polymers, powder to wire. A usual saying is that a material only is as strong as the bond holding it together.

Depending on the exact process, the part will get more or less porous. For some processes and or applications of the part it is therefore necessary to further consolidate material after finished build to improve the material characteristics. For UV-curable plastics it could be curing in UV-oven while for metals it could involve furnace post processing with or without infiltration.

When it comes to metals the achieved properties has much to do with metallurgy, in which way it is heated, to which temperature and how the part is cooled or even how each layer is cooled down. There are at least 50 factors which influences the melting alone. Having a machine with a good process control is therefore key to achieve the wanted result. One review on metal AM and material characteristics can be found in [18], it might be dated when it comes to exact numbers on material strength as it was published in 2012 but the basic concept applies.

2.1.2 Sustainability

Sustainability is a quite wide notion. From a manufacturer's point of view it could involve looking at every process from the extraction of resources needed in creating and developing a product to the effects of the disposal. Some aspects specific to machine processes include energy consumption, scrap rate, occupational safety and health, etc. It is important to also consider the use of the printed part when compared to its alternative, it could involve better utilisation of material, optimising supply chain, possibly decreasing energy consumption, etc. [19].

> *"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."* [20].

2.1.2.1 Suggested Literature

A lot more could be said on sustainability, for example; in [21] a framework was developed for analysing environmental impact when using the powder bed fusion process; the environmental impact was evaluated in [22] for the directed energy deposition process; in [23] a comparison on sustainability between injection moulding and AM is made; and in [19] a literature review on societal aspects is presented.

2.1.3 AM Cost Breakdown

It can be problematic to find the real cost involved in AM systems, operations and also implementation of AM [14, p. 197]. The studies published to this date are often biased to specific machines, to having a machine in-house and only using just one test geometry for the print.

According to [26], the total cost of an advanced manufacturing system could be categorised into expenses that are either relatively well-structured or ill-structured. See figure 2.1. It separates between costs that are a bit more predictable linked to the productivity (such as labour and material) and costs that are more uncertain during the process (such as preventive actions, failures in the process or even in the inventory). [24].

The cost will naturally also vary depending on if an in-house AM machine is available or if the printing is outsourced – regardless, it is good to know the cost drivers of AM.

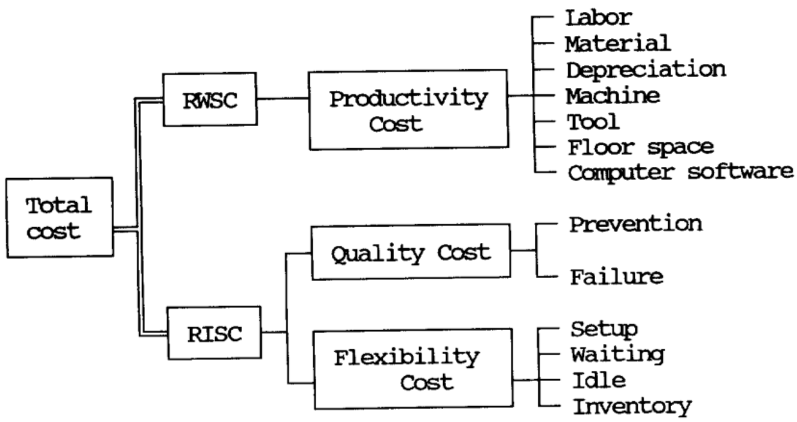


Figure 2.1 The total cost could be divided into relatively well-structured costs (RWSC) and relatively ill-structured costs (RISC) [26, p. 442].

2.1.3.1.1 Suggested Literature

A good literature review and discussion on the costs and cost effectiveness of AM was published in December 2014, see [24]. To read more on the costs involved in implementation some hints are also given in chapter 7. In 2012 an article was published in which the cost drivers of AM are analysed in detail for one machine in metal AM to understand how various parameters might affect the cost. Another article was published in 2013, [25], which looks into quality management for one of the plastic AM process, selective laser sintering.

2.1.3.2 Relatively Well-Structured Costs

Productivity costs are tangible costs required in making a component. A few examples are provided in [24, pp. 15-24].

- AM material cost per kilogramme are usually much higher than material in conventional manufacturing, it might be better utilised though.
- The machine cost could be a substantial part of the cost of printing a part, as depreciation time of a machine usually is only 5-7 years. The cost of the printed part will naturally depend on the build time and how expensive the machine was.
- How effective a machine is in build time will depend on the geometry of the part and the process in the machine. It will depend on how easy the chosen material is to process[3], the geometry of the part[4].
- Both the build envelope and the envelope utilisation affect the costs and the energy consumption.
- The energy consumption is considered an important aspect when choosing whether or not to use AM. [24] also discussed some studies that has been made on specific machines, with various outcomes on energy consumption.
- The AM processes are usually fully automated. Though afterwards it is often required to do some post-processing, therefore the labour could still be a substantial part of the cost.

2.1.3.3 Relatively Ill-Structured Costs

The relatively ill-structured costs consists of quality costs (such as prevention and failure) and flexibility costs (such as setup, waiting, idle, inventory). These can be further viewed as either process defects or product defects [26, p. 442].

In [24, pp. 12-15], focus was on the costs hidden in the supply chain as defects in processes to streamline productivity. By having an appropriate AM machine at the right place, costs in transportation can be cut – especially if the whole production is closer to the customer. By smaller links in the supply chain, vulnerability to supply chain disruption can be avoided. Process improvements could also involve costs in waiting on machine instalment, setting up and waiting on material supply, changing of material[5], cost when overstocking, etc.

There could also be a defect in the printed part as a result from a mishap in the machine or in the handling afterwards. For a successful print it might be crucial to get the orientation of the part right in the machine and be aware of design constraints for the specific AM machine. These aspects also means that when a component has been printed a few times, the success ratio might be higher and the process more streamlined. [27].

---

[3] Steel for example takes double the time for a finished build relatively to aluminium, as learned during the case study in the development of a metal AM component.

[4] It will depend on geometry, placing of eventual cavities and material – travel patterns of the machine.

[5] If a machine offers the possibility to print in various materials, the time for changing it could for some cases take some minutes or even days depending on the machine.

2.2 Binder Jetting

> *"Additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials"* – definition of the binder jetting process category [5, p. 2].

Binder jetting (BJ) is typically based on a powder bed as seen in figure 2.2. See table 2.1 for an overview. When the BJ was originally developed it was named 3D printing – today however 3D printing is often used synonymously with all AM processes.

A typical BJ process is; (a) powder is distributed on the whole build surface, (b) binder is distributed to create the part's cross section which causes the material to consolidate chemically, (c) the build plate is lowered for the next layer and (d) the process is repeated until the build is finished. A heated build chamber could speed up the process, making the adhesive cure more rapidly. [28; 29].

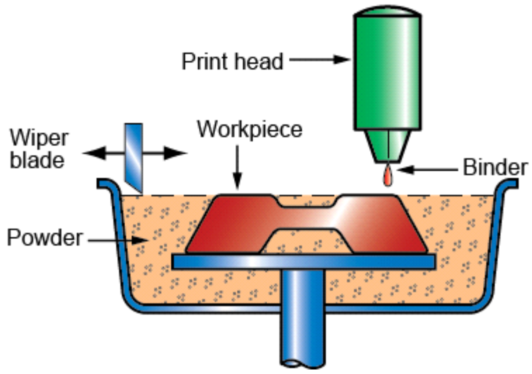


Figure 2.2 A basic schematic of the binder jetting process category. CES EduPack 2015. Image courtesy of Granta Design Ltd (Cambridge, United Kingdom). [29].

When the build is completed, the component can be removed from the machine and separated from the residue powder. Before handling, the component often has to cure (depending on the adhesive) and cool down. And as the component only will be as strong as the glue holding it together, the structural and mechanical properties might have to be improved by additional consolidation processes such as furnace sintering with or without infiltration. All of this means that though the BJ process is relatively quick, the necessary post processing might increase the lead-time considerably. [5; 28; 29]; [17, pp. 35-37].

Table 2.1 Overview on the binder jetting process. Based on [17, pp. 35-37, 64]; [28]; [29].

Possible materials	Polymers, polymer blends, composites, metals and ceramics. Some examples are stainless steel, copper, tungsten, Inconel, nickel, ABS, PA, PC, glass.
Some uses	Modelling and prototyping. Low volume manufacturing. Sand moulds and cores for casting. Investment casting patterns. BJ is not always suitable for structural parts.
Necessary post processing	*In general:* Depending on the machine and the geometry it might be necessary to first let the part cool down in machine, let the adhesive set. Then the residue powder can be removed. *For metals:* It might be necessary to remove support structure. The part could be further consolidated through e.g. furnace post processing, with or without infiltration.
Machine manufacturers	3D Systems, Digital Metal, ExOne, Voxeljet Technology GmbH

2.3 Directed Energy Deposition

> *"Additive manufacturing process in which thermal energy is used to fuse materials by melting as they are being deposited"* – definition of the directed energy deposition process category [5, p. 2].

In the directed energy deposition process category, material is basically fed into a melt pool created with thermal energy. The name laser cladding is often used as a synonym to the directed energy deposition category. See figure 2.3 for a basic schematic of the process and table 2.2 for an overview. [17, p. 41].

There are several variants on processes; the build material could be either metal powder or wire; the thermal energy is often a laser beam, though it could also be e.g. an electron beam[6] or a plasma welding torch[7]; and hybrid machines have a high precision mill integrated in the process. When powder is used the directed energy deposition could also be referred to as blown powder. [17, pp. 41-42]; [29].

Technologies under the directed energy deposition category are often combined with multi-axis motion systems and robotic arms, meaning that the build is not limited to horizontal layers. The build could easily follow complicated surfaces on already existing objects for repairs. [17, p. 41]. Or could be used as a second operation to other manufacturing methods to build in more complexity [28].

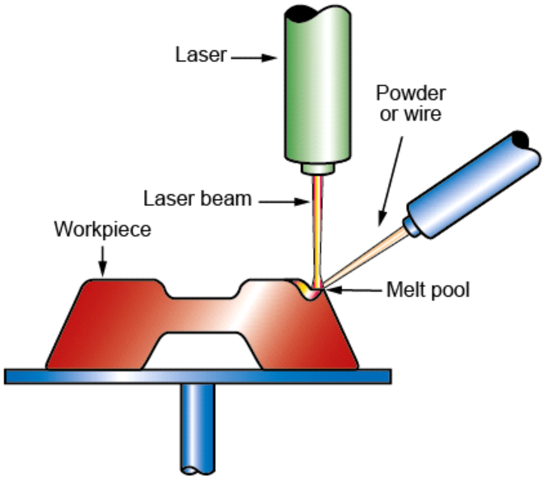


Figure 2.3 A basic schematic of the directed energy deposition process category. CES EduPack 2015. Image courtesy of Granta Design Ltd (Cambridge, United Kingdom). [29].

[6] Sciaky sells machines using electron beams.

[7] This is on a research level, no commercial machine available.

Table 2.2 Overview on the directed energy deposition category. Based on [17, pp. 41-42, 64]; [28]; [29].

Possible materials	Typically metals and graded metals, such as cobalt chrome and titanium. Hybrid metals are also possible but not typical for this process. Polymers and ceramics are also possible but not usual. DMG Mori can print stainless steel, nickel-based alloys (Inconel 625, 718), tungsten carbide matrix materials, bronze and brass alloys, chrome-cobalt-molybdenum alloys, stellite and weldable tool steel.
Some uses	Could be used for repairs and second operations to add complexity.
Necessary post processing	N/A
Variants on process	Electron beam direct manufacturing (EBDM) Direct metal deposition (DMD) Ion fusion formation[a] Laser consolidation Laser engineered net shaping (LENS)
Machine manufacturers	*Powder based:* BeAM, Optomec, RPM Innovations, and Trumpf. *Wire based with electron beam:* Sciaky. *Powder based hybrids:* DMG Mori Seiki, Hermle, Hurco, Hybrid Manufacturing Technology and Mazak.

[a] Not commercialised, not yet at least.

2.4 Material Extrusion

> *"Additive manufacturing process in which material is selectively dispensed through a nozzle or orifice"* – definition of the material extrusion process category [5, p. 2].

In the material extrusion process category, the part is built out of material that is dispensed through a nozzle or an orifice. See table 2.3 for an overview on material extrusion.

The typical steps of processes in this category are; (a) material is extruded on the cross section of the part, often a with partly hollow structure on the inside of the component and support structure for undercuts, (b) build plate is lowered to give room for the next layer and (c) these steps are repeated until the build is finished.

The arguably most prominent technology that goes under the material extrusion process category is the fused deposition modelling (FDM). FDM uses spools of thermoplastic filament which is melted at the tip of the nozzle to build up the part, see figure 2.4. It could be one or several nozzles feeding the material, printing in several materials or printing support material of another material that more easily can be removed. [17, p. 33]; [29].

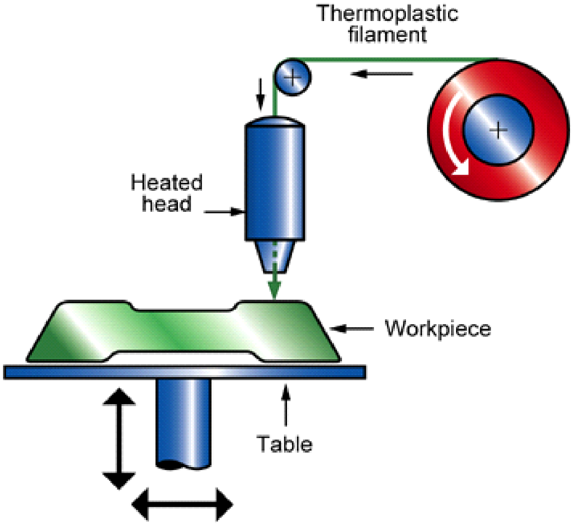


Figure 2.4 A basic schematic of the material extrusion process using FDM technology. CES EduPack 2015. Image courtesy of Granta Design Ltd (Cambridge, United Kingdom). [29].

Other technologies also belonging under the material extrusion uses viscous liquids or slurries in syringes or industrial hoppers, in which several materials could be printed; e.g. ceramics, composites, metal filled clays, concrete and food. One company, Arburg, has developed a technology using standard injection moulding granulates extruded with injection moulding equipment to build up the part [30]. [17, p. 33].

Table 2.3 Overview on the material extrusion category. Based on [17, pp. 33, 64]; [28]; [29]

Possible materials	Polymers and polymer blends. Thermoplastics (e.g. ABS, ASA, Nylon, PC, AB), ceramics, composites, metal filled clays, concrete and food.
Some uses	Modelling and prototyping. Sand moulds and cores.
Necessary post processing	Depending on the machine and the geometry it might be necessary to let the part cool down in machine and remove support material.
Machine manufacturers	Aleph Objects, Beijing Tiertime, MakerBot Industries, Stratasys and Ultimaker.

2.5 Material Jetting

> *"Additive manufacturing process in which droplets of build material are selectively deposited"* – definition of the material jetting process category [5, p. 2].

Processes belonging to the material jetting category selectively deposits droplets to build a part, usually layer wise in a vertical direction. See figure 2.5 for a basic schematic and table 2.4 for an overview of the category. Some variants on machines includes the following. [17, pp. 34-35].

- Machines typically have two or more print heads, one to create a support structure and the other/s to actually build the part. If there are several nozzles to build the part, it is possible to use several materials joined together in the process and or graded materials for the part.
- Hybrid machines from Solidscape combines thermoplastic material jetting with high-precision milling for the contours of each layer to achieve better surfaces, particularly used for casting small metal parts.
- Direct-write technology uses atomized nanoparticle-size materials with an inert gas jetted in a focused beam to form droplets. Machines using this technology could print both metals and non-metals enabling e.g. electrical circuit boards.
- Voxel8 has machines which combines material jetting (more specifically direct-write technology) with the material extrusion process FDM, especially intended for electrical circuit boards.

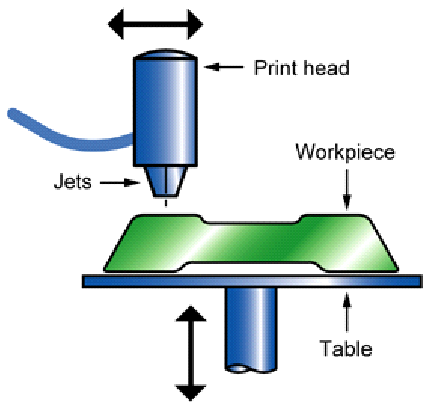


Figure 2.5 A basic schematic of the material jetting process category. CES EduPack 2015. Image courtesy of Granta Design Ltd (Cambridge, United Kingdom). [29].

Table 2.4 Overview on the material jetting category. Based on [17, pp. 34, 35, 64]; [28]; [29].

Possible materials	Some types of polymers, polymer blends, composites and metals are possible. On some machines it is possible to print several materials in one part and even graded materials.
Some uses	Typically photopolymers and wax-like materials to use as investment casting patterns. As you will see in chapter 3, it is also often used in direct part manufacturing for modelling and prototyping purposes. Some machines also enables printing of electronic circuits.
Necessary post processing	Depending on the machine and the geometry it might be necessary to let the part cool down in machine, cure in UV, remove support material and or clean.
Machine manufacturers	Stratasys, Solidscape and 3D Systems. *Direct-write technology:* Optomec, Nscrypt and Voxel8.

2.6 Powder Bed Fusion

> *"Additive manufacturing process in which thermal energy selectively fuses regions of a powder bed"* – definition of the powder bed fusion process category [5, p. 2].

In the powder bed fusion process category, powder is hit by thermal energy to create cross sections of a part. See table 2.5 for an overview.

A typical process is; (a) powder is distributed on the whole build surface, (b) thermal energy hits the area of the part's cross section which causes the material to consolidate by melting, (c) the build plate is lowered for the next layer and (d) the process is repeated until the build is finished. [28]. There are several processes based on this technology.

Selective laser sintering (SLS) processes using plastics is the oldest variant within the powder bed fusion category. See figure 2.6 for a basic schematic. More recently, Lotus F1 and Boeing have developed a technology (not commercialised) which uses recycled carbon fibre in smaller and bigger particles combined with plastics, this is said to provide a more uniform structure [31].

Direct metal laser sintering (DMLS) technology prints in metals and ceramics and functions similarly to SLS, see figure 2.6. The result with DMLS is denser than SLS for metals and ceramics, it is possible to do infiltration to make it fully dense if needed. [29].

Selective laser melting (SLM) technology prints in metals and ceramics and uses the same basic schematic as SLS, see figure 2.6. The result is a fully dense part without the need of infiltration. Though as the temperature of the part increases during the build, the resulting material characteristics are very different from cast materials. [29].

Electron beam melting (EBM) technology uses a high-energy electron beam instead of a laser, see figure 2.7. It has more uniform heat handling than SLM meaning that it is possible to achieve material characteristics similar cast materials. [29].

Hybrid machines exists from the companies Matsuura and Sodick that combine processes using powder bed fusion with a high precision mill, trimming the contour for each layer to achieve a better surface finish and tolerances directly out of the machine. [17, pp. 39-41].

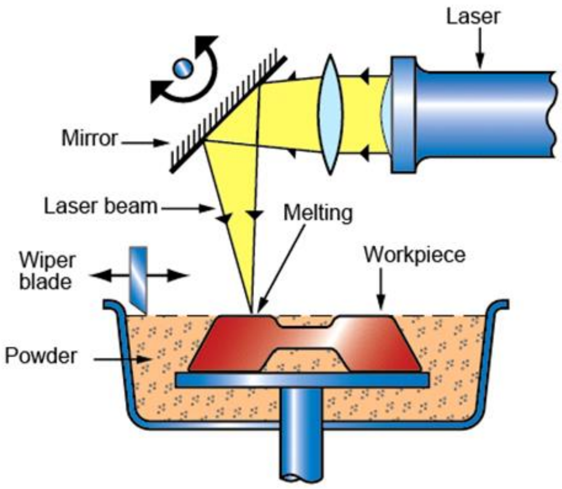


Figure 2.6 A basic schematic of the powder bed fusion process using the SLS, DMLS or SLM technology. CES EduPack 2015. Image courtesy of Granta Design Ltd (Cambridge, United Kingdom). [29].

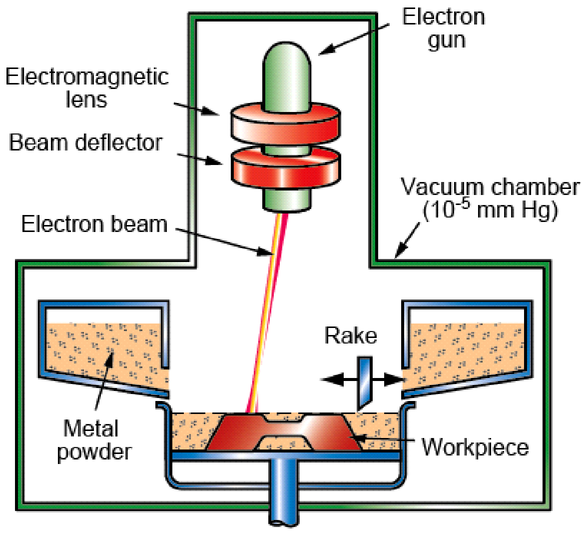


Figure 2.7 A basic schematic of the powder bed fusion process with the EBM technology. CES EduPack 2015. Image courtesy of Granta Design Ltd (Cambridge, United Kingdom). [29].

Table 2.5 Overview on the powder bed fusion category. Based on [17, pp. 39-41, 64]; [28]; [29].

Possible materials	Polymers, polymer blends, composites, metals and ceramics. *SLS:* Nylon *DMLS, SLS, SLM*: stainless steel, titanium, aluminium, cobalt chrome, steel *EBM:* titanium, cobalt chrome, stainless steel, aluminium and copper
Some uses	Modelling and prototyping. Are used increasingly for end use products. Investment casting patterns.
Necessary post processing	Depending on the machine and the geometry it might be necessary to first let the part cool down in machine. Afterwards residue powder can be removed. *For metals:* When it comes to metal support material needs to be removed and it could be further consolidated through e.g. furnace post processing, with or without infiltration.
Technologies	Electron beam melting (EBM) Direct metal laser sintering (DMLS) Selective laser melting (SLM) Selective laser sintering (SLS)
Machine manufacturers	Many sells machines based on powder bed fusion. Some examples: 3D Systems, Arcam, EOS, Matsuura, SLM Solutions, ReaLizer, Renishaw and Sodick.

2.7 Sheet Lamination

> *"Additive manufacturing process in which sheets of material are bonded to form a part"* – definition of the sheet lamination process category [5, p. 3].

In the sheet lamination process category, sheets of material are joined together to build a part. There are at least two processes, ultrasonic additive manufacturing (UAM) and laminated object manufacturing (LOM). [29]. See table 2.6 for an overview on the sheet lamination category.

UAM, as can be seen in figure 2.8, joins material by a sonotrode. The sonotrode vibrates in high frequencies which causes the layers to melt (by friction). To ease the post processing and to achieve better surface finish it could be combined with a mill head. [17, p. 37]; [29].

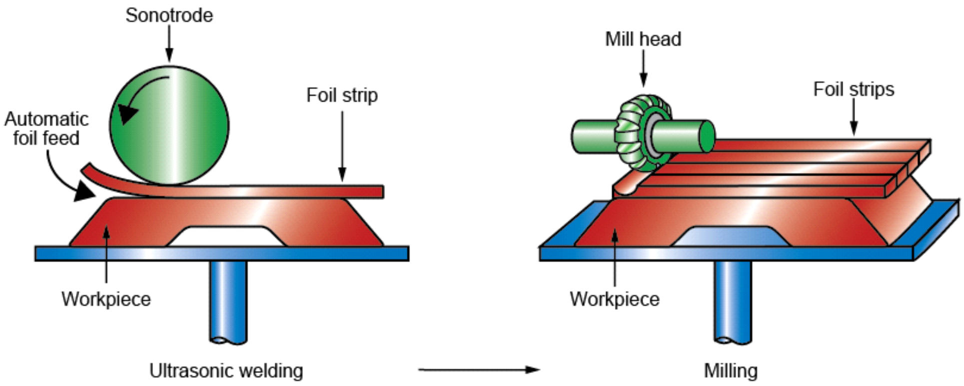


Figure 2.8 A basic schematic of the sheet lamination process using UAM technology. CES EduPack 2015. Image courtesy of Granta Design Ltd (Cambridge, United Kingdom). [29].

LOM instead uses sheets pre-laminated with heat sensitive adhesive, see figure 2.9. The layers is then heated selectively and the contour of the cross section can be cut e.g. using a knife or cutting by laser. Undercuts could be created by cutting tiles or cubes in the material that after the build easily could be removed. [17, p. 37]; [29]; [32, p. 208].

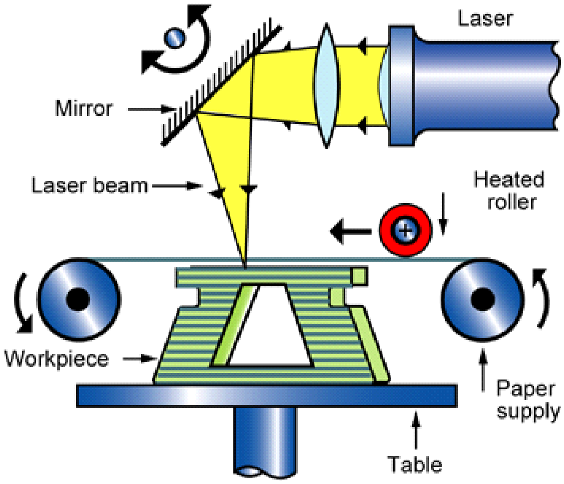


Figure 2.9 A basic schematic of the sheet lamination process using the LOM technology. CES EduPack 2015. Image courtesy of Granta Design Ltd (Cambridge, United Kingdom). [29].

Table 2.6 Overview on the sheet lamination category. Based on [17, p. 64]; [28]; [29]; [31]; [32, p. 210]

Possible materials	Polymers, polymer blends, metals and hybrid metals. Metals consolidated ultrasonically, craft paper coated with adhesives, standard sheets of papers with adhesives and carbon fibre fused with plastics. LOM could be integrated with colour.
Some uses	*LOM:* Could be a good substitute for wooden patterns in sand casting. LOM is typically used for models or prototypes. *UAM:* is typically used for repairs.
Necessary post processing	Depending on the machine and the geometry it might be necessary to let the part cool down in machine, cure, remove support material and or clean.
Technologies	Laminated object manufacturing (LOM) Ultrasonic additive manufacturing (UAM)
Machine manufacturers	*LOM:* Helisys and Mcor Technologies. *UAM:* Fabrisonic.

2.8 Vat Photopolymerization

> *"Additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization"* – definition of the vat photopolymerization process category [5, p. 3].

In the vat photopolymerization process category, a part is built chemically with liquid photopolymer that is cured selectively with light. See table 2.7 for an overview. There are some variations in the machines. [17, p. 38]; [29].

- The light beam could for example be point wise or even a complete cross section of the part at once.
- The light beam could be a laser, lamp or LED.
- The light could be either under the liquid container or from above, meaning that the component either can be built from the bottom-up or top-down.

Stereolithography apparatus (SLA) technology was the first AM technology to be commercialised. It uses an ultraviolet laser that scans through the cross section. See figure 2.10.

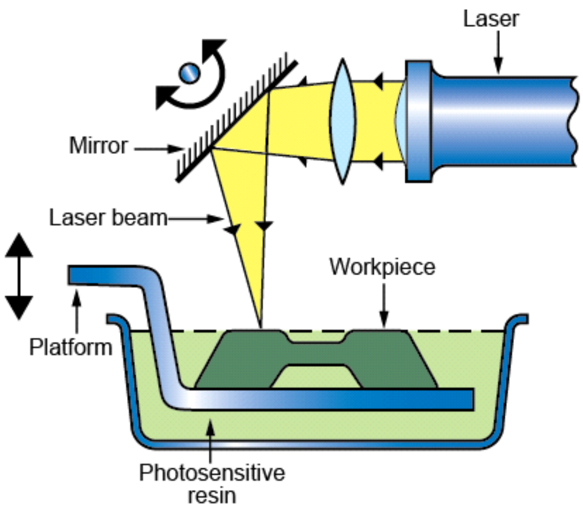


Figure 2.10 A basic schematic of the vat photopolymerization process using the SLA technology. CES EduPack 2015. Image courtesy of Granta Design Ltd (Cambridge, United Kingdom). [29].

Masked projection stereolithography (MPSLA) technology instead projects a whole cross section at once. See figure 2.11. This process is often also referred to as DLP, though strictly speaking DLP is actually a part of some of the MPSLA machines and not a process in itself. [29].

A new technology belonging to the MPSLA is CLIP, developed by Carbon3D. It is said to be 25 to 100% quicker than other AM machines, part of the reason behind this is their solution which enables a continuously moving platform. The part is pulled up from the bottom of the container were it is cured gradually with a light underneath which lit through a special window (transparent to light and permeable to oxygen) and a dead zone which separates the part which is being built from this window. [8]. See figure 2.12.

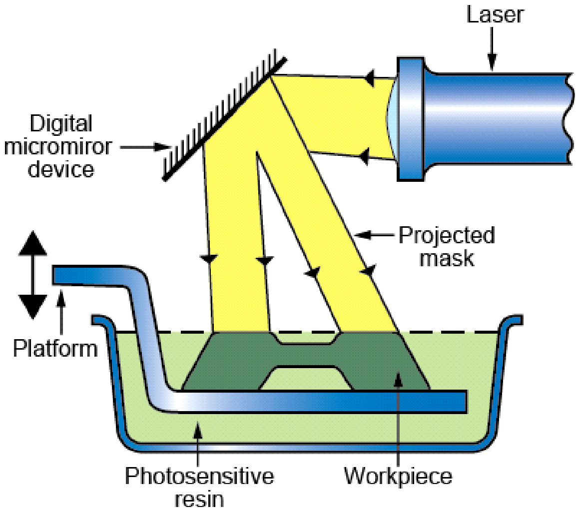


Figure 2.11 A basic schematic of the vat photopolymerization process using the MPSLA technology. CES EduPack 2015. Image courtesy of Granta Design Ltd (Cambridge, United Kingdom). [29].

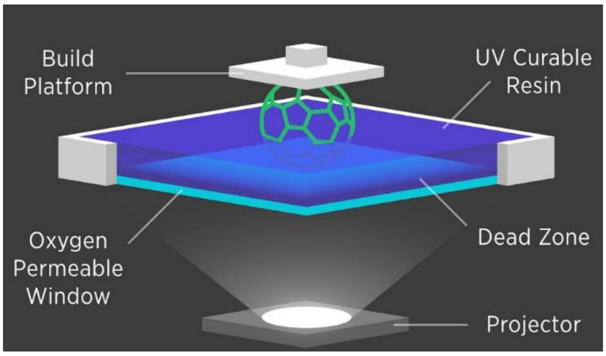


Figure 2.12 A basic schematic of the CLIP technology [33].

Table 2.7 Overview on the vat photopolymerization category. Based on [17, pp. 64, 68]; [28]

Possible materials	Polymers, polymer blends and ceramics.
Some uses	Investment casting patterns.
Necessary post processing	Often requires post curing in UV, removal of support structure and cleaning.
Machine manufacturers	3D Systems *MPSLA*: Asiga, Carbon3D, DWS, Envisiontech, Lithos, Prodways and Rapid Shape

2.9 Future Work

Every now and then machines are improved and new technologies brought to life. With every new advancement; machines could get better, faster, cheaper, etc. allowing for more uses. It is important to keep up to date not to miss any opportunities and not forgetting the already existing machines.

Going deeper into the materials, sustainability and economics are unfortunately beyond the scope of this thesis, and the risk is that whatever information you find is either biased or dated. It is important nonetheless.

For the future work it might be good to document the different processes in even greater detail for future references in outsourcing our investing in a machine. Some details missing in this chapter are the associated typical design constraints for each of the processes, build volume, speed, costs, etc. This chapter could also go into even greater details on different machines.

3 Benchmark

Benchmarking is an important tool in becoming and staying competitive. It aids in recognising the maturity and potential of additive manufacturing. By studying what others already have done some clues on the automotive applications might be gained, even or especially if the benchmark is not on the same industry.

3.1 Introduction

AM is increasingly used beyond modelling and prototyping, at least if you believe the information flow of the last couple of years. Naturally you should differentiate between companies. There is the technology leader who takes risk to harvest the profit of being early, these are the ones that usually shows up in the news first. [16, p. 244]. Then there are the companies who takes less risk waiting for the technology to mature. By the time it has reached the plateau of productivity in the hype cycle it has been adopted by 20-30% of the believed audience and only the laggards are left who to some extent benefits from all research and information publically available at that time but misses out on the profits of being quicker to adopt. [10].

Finding benchmark applications in AM is problematic, not everyone show and tell. The competiveness of the automotive industry deters into secrecy even if ahead or not. Not all industries are as secretive though. Learning from other industries instead could prove invaluable.

There is a great incentive from machine suppliers to showcase what is possible in order to sell more machines and materials. Though even if they are aware on suitable applications for the automotive industry they sometimes cannot say due to non-disclosure agreements (NDA) and are left with the few showpieces that they are allowed to show. As their objective is to sell machines, their info is likely biased.

Even if you see a result that you like it might be tricky to achieve the same outcome as it is dependent on the machine, machine settings, material, orientation of component and other factors which might influence. Also, the machine or the material might not be available for everyone as developers thereof might have signed an exclusivity contract to certain companies – this is frequent in new development were companies co-develops and or sponsors development [4]; [34].

In the coming text, the benchmark on some of the publically available information from the automotive industry, aerospace industry and a separate text on the tooling side are presented.

3.2 Automotive

In this section, publically available information on AM in passenger cars and the motorsport sector are discussed.

3.2.1 Passenger Cars

3.2.1.1 Audi (Part of the Volkswagen Group)

Under the management of Prof. Dr. Waltl the 14 toolmaking divisions inside the Volkswagen Group, which Audi is part of, are creating vital synergies for the implementation of metal and sand AM. When creating a 1:2 scale model of the "Auto Union Typ C" as seen in figure 3.1, all the metal parts were fabricated with metal AM. [35].

> *"We are pushing forward with new manufacturing technologies at Audi Toolmaking and at the Volkswagen Group* […] *Together with partners in the area of research, we are constantly exploring the boundaries of new processes. One of our goals is to apply metal printers in series production."* – Prof. Dr. Waltl [35].

Figure 3.1 The Auto Union Typ C scale model [35].

Audi has not revealed which machines they have nor which machines are used for this vehicle. From their press release both the method and materials are stated. Audi Toolmaking are using Direct Metal Laser Sintering (DMLS) machines, with the possibility to print in aluminium and steel. "At present, this process can be used to produce shapes and objects with a length of 240 millimeters and a height of up to 200 millimeters". [35].

3.2.1.2 Bentley (Part of the Volkswagen Group)

Bentley has equipped their design studio with printers from Stratasys, using an Objet30 Pro desktop printer and the multi-material printer Objet500 Connex. These printers allows the design team to produce both full and small scale models for "for assessment and testing prior to production on the assembly line". Almost every part is printed prior to production. [36].

> *"The accuracy of the Objet30 3D Printer enables us to take a full-size part and scale it down to produce a one-tenth scale model* […] *Once we have approval at this scale, we can move onto our larger Objet500 Connex 3D Printer to produce one-third scale models, full-sized parts as well as parts that combine different material properties without assembly."* [36].

3.2.1.3 BMW

BMW has a long history of using AM. In 1990, the Munich plant was the first customer of the SLA machine STEREOS 400 from EOS. In 1993, an EOSCAN 100 was installed at BMW and in 1995 BMW in Landshut installed an EOSINT S 350 for printing sand cores/moulds directly for their cast metal parts. The year after, a bigger EOSINT S 700 was also installed in Landshut. [37]. In 2007 BMW released a video showing how they are using SLS with the material polyamide to produce internal prototype parts for a new door. In the same video, metal door hinges were made in a Concept Laser M3 and an EOS STEREOS 600 MAX were utilised within their F1 team. [38].

> *"Rapid prototyping serves the purpose of providing prototype parts to the relevant departments within a very short time frame, so that they can solve their problems very quickly."* [38].

Yet another video was released in 2011 [39], this time showing off AM in their so called "Plant Zero". Plant Zero is located at BMW's Research and Innovation Centre in Munich and is their experimental vehicle shop. In this video aluminium parts are produced on a Concept Laser M3 machine. If this is the same machine as in the previous video is not known.

> *"The targeted use of innovative additive procedures at an early stage has made us one of the pioneers and leaders in 3D printing over the past years. At the BMW Group Technology Office in Mountain View, Silicon Valley/USA, we are now even conducting a first test run with the new CLIP (Continuous Liquid Interface Production) technology. Components made with additive manufacturing give us a lot of freedom in the forming process; they can be produced both quickly and in appropriate quality. We see major potential for the future application in series production as well as for new customer offerings, such as personalized vehicle parts, or the spare parts supply."* [9].

For their in-house customers, the personnel gets 25,000 prototype request yearly for approximately 100,000 parts. Parts range from "small plastic carriers to design samples and chassis components for functional tests”. These parts can be produced within days depending on part size and method. [9].

BMW has also been using FDM at their plant in Regensburg, Germany, for their vehicle design prototyping. Beyond prototyping, BMW is taking the application into manufacturing aids. At the division of jigs and fixtures, a FDM machine has been used to build hand-held tools for the assembly line and testing. See figure 3.2. [41].

Figure 3.2 A hand-held fixture for mounting badges on the rear trunk lid [40].

> *“BMW has determined that the FDM process can be an alternative to the conventional metal-cutting manufacturing methods like milling, turning, and boring. FDM is taking on increasing importance as an alternative manufacturing method for components made in small numbers.”* [41].

For these tools, engineers at BMW have found that the use of FDM gives several advantages such as cost reductions, lessened lead-time, bigger design freedom, lower weight, improved balance and functionality. See table 3.1 for one example. This often results in designs that cannot be manufactured any other way.

> *“In one example, BMW reduced the weight of a device by 72% with a sparse-fill build technique. Replacing the solid core with internal ribs cut 1.3 kg (2.9 lbs) from the device. This may not seem like much, but when a worker uses the tool hundreds of times in a shift, it makes a big difference.”* [41].

Table 3.1 One example on how FDM compares to CNC-machining according to BMW [41].

Method	***Cost***	***Lead-time***
Traditional CNC-machining (Aluminium)	$420	18 days
Fortus System (ABS-M30 Thermoplastic)[a]	$176	1.5 days
Savings	$244 (58%)	16.5 days (92%)

[a] Several other materials are possible to use with the Fortus System [42].

To decide on when to use FDM for manufacturing aids, BMW follows a flow chart based on the factors “temperature, chemical exposure, precision, and mechanical load”. Many of the tools used at BMW were reportedly satisfying these factors in 2013 when the article was first published [41]. This flow chart does not seem to be publically available though and is most likely based on BMW’s specific needs and only applicable to specific machine/s.

Another tool that has been developed at BMW, is “a flexible finger cot”. This ergonomic tool protects the worker’s thumb joints against excess strain when fitting rubber plugs. Each cot is unique – customised for each worker, made possible by scanning each worker’s hand with a 3D-scanner. The cots are then manufactured with one of BMW’s SLS machines. [9].

> *“In order to prevent the unnecessary overstretching of the thumb joint, the finger cots made of thermoplastic polyurethane are put over the thumb like a second skin. Right at the thumb joints, the assembly aid is open to allow the thumb to move without restriction. At the back of the thumb, though, the plastic material is reinforced. If the thumb is stretched, as in a ‘like it’ gesture, the reinforced elements collide, forming a stable splint. This way, the effort needed to press in the plug is spread across the entire thumb, down to the carpus.”* [9].

Back in 2010, BMW motorsport developed a water pump wheel in aluminium instead of the usual plastic ones used in road cars. By using the design advantage of AM, the hydrodynamics (i.e. flow of the water) could be optimised. Today over 500 water pump wheels have been produced and used in their DTM race cars, as well as in the Z4 GT3 race cars. During the five years that this new pump wheel has been used, none has failed during a race, proving that the design has endured the workload. [43]. See figure 3.3.

Figure 3.3 The water pump wheel made by BMW [9].

3.2.1.4 Ford Motor Company

Ford is yet another company with a long history of using AM. In 1988s, Ford invested in a SLA machine and is today using several AM processes, such as SLA, SLS, FDM, CLIP and BJ. These processes are used within Fords five “3D prototyping centers” [44; 45; 46]. Three centres are located in the U.S, the other two are located in Europe. Today 14 different machines produces in total 20,000 parts yearly at Ford’s facility in Dearborn Heights, Michigan. Some of these parts are used in real life testing, such as “engine air intake manifolds and oil pans” which are made out of a “special nylon” to be able to do functional testing for several thousand kilometres. The results are then used to adjust the production parts if needed. [44].

With the BJ machines, sand moulds are produced for the making of metal prototypes. See figure 3.4. A single BJ print can take everything from a week up to a four weeks, depending on the size of the job. “Conventional sand moulds would take eight to ten weeks.” [44].

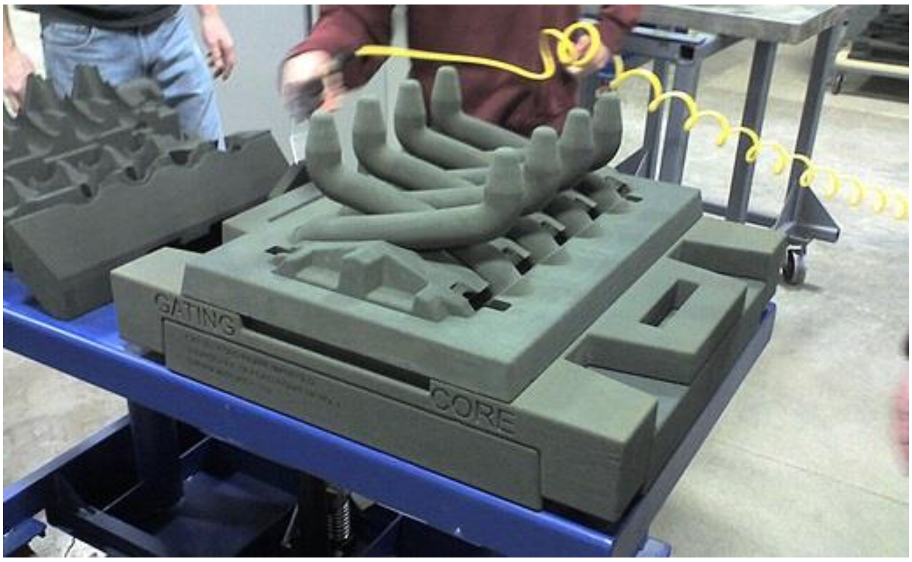


Figure 3.4 Sand patterns for an air intake manifold [47].

> *"Companies like 3D Systems and Stratasys are spending huge amounts of money on development. So not only are machines and materials getting better, but the process is getting faster and it's helping drive the overall cost down. In fact, without 3D printing, the Ford Motor Co. simply would not be able to meet its new model vehicle build deadlines. The company is today dependent on 3D printing to invent new vehicle parts. Everybody wants to know how much 3D printing has saved in dollars, but when you're talking prototypes, it's time. What would bringing a product to market a month early do for you? That's millions of dollars. It's not something that's easily measured.”* [44].

In search of even faster AM technology, Ford has secured a partnership with Carbon3D [45]. Carbon3D has developed a new technology known as CLIP. Instead of printing the parts layer by layer, CLIP "grows" them instead. This results in print jobs being "25 to 100 times faster than traditional 3D printing". Carbon3D has not yet released this technology to the market, but it is expected to be released during the first half of 2016. [48].

> "*The materials Carbon3D uses to create objects are still being tested as to their performance in different environments. Ford wouldn't want to put materials in cars that can dramatically alter in strength or shape depending on the weather, for example. "* [45].

Ford especially point out that CLIP might be used in making relatively durable moulds, perhaps as a temporary before metal tooling. This would reduce the time needed for the production of the moulds considerably, as it usually takes two to three months to produce metal moulds and with CLIP it would hardly take one day. [45].

3.2.1.5 General Motors (GM)

During 2011, the machine manufacturer 3D Systems released three videos showing how GM is using AM within their pre-production. By using at least 16 machines in total (SLA and SLS machines) GM is producing over 20,000 parts yearly. GM is also a beta site testing facility for 3D Systems, meaning that GM is among the first ones to get any new machines or updates for their fleet of machines. [49; 50].

3.2.1.6 Honda

Honda's racing department had a very tight deadline for the development of one their engines during 2010, in which they modified a production engine to a race engine (Honda Racing 2.8 litre twin-turbo). They already had a plastic AM machine from 3D Systems for prototyping purposes and decided to complement it with the wax printer ProJet 3000 CPX RealWax^{TM}. [51].

Honda uses the ProJet 3000 CPX primarily to make patterns for investment casting. For this application they managed to reduce time to testing from an average of eight weeks to four, allowing for more iterations on design. Honda is now incorporating the ProJet 3000 CPX printer in every new engine project, not just for racing (it does not say in the article, but perhaps only for prototyping when it comes to the regular engines). For the HR25TT engine, the exhaust manifolds, the rocker arm housings and the oil filter housing were produced using this AM machine. [51]. See figure 3.5 for two examples.

Figure 3.5 Metal parts fabricated through investment casting using printed injection wax tools to produce the master pattern [51].

3.2.1.7 Hyundai & KIA

Hyundai Mobis makes original and aftermarket parts for the automotive industry, including Hyundai and KIA. They were using just one FDM system from Stratasys which they are run at 91% of capacity but they still had to outsource 60% of their prototypes. To further decrease lead-time and thereby being able to iterate more, they decided to install another machine under Stratasys Fortus series. The first one reportedly paid off in under 20 months. [52].

One example of when they have used their Fortus machines is for the Kia Spectra. They made a prototype of the instrument panel to design verification to test fit. Before mounting in the assembly, it was tested for dimensional accuracy with a coordinate measuring machine, CMM. 27 design flaws were found when mounted in the assembly, all easy to fix but costly and time consuming if they had not been found in time. [52].

> *"Dimensional accuracy and dimensional stability were critical for the design verification. The FDM system, with its ABS plastic, gave us both. Over a length of 1382 mm, the greatest deviation was just 0.75 mm." [52].*

3.2.1.8 Jaguar Land Rover

Jaguar Land Rover has several machines in SLA and polymer material jetting technology. In 2008 they added another material jetting machine, Objet500 Connex.

With the ability to print rubber-like materials and fully functioning mechanisms, the first project for the Objet500 Connex was to produce a complete air ventilation assembly. The assembly was printed in a single process as a working part. [53].

Figure 3.6 Multi material parts printed in one process [53].

Jaguar Land Rover produces 30,000 prototype parts every year, most of them using SLA technology. For the resin-based parts, more and more are produced on the Objet500 Connex system, which accounts for more than 30% of the resin based parts. [53].

Even though the machine has capabilities to use several materials in one print, the Objet500 Connex printer is mostly used for the production of single-material rigid parts owing its speed and easy post-processing. Some of the multi-material uses for Jaguar Land Rover are "styling and human/machine interface concepts, such as knobs, switches and key fobs", but could also be as simple as a cover with a rubber seal. See figure 3.6. [53].

3.2.1.9 Koenigsegg

Koenigsegg uses AM for both prototypes and in direct part production for end use products.

Previously, they outsourced all of their AM prototyping needs. This added several days to the lead-time which hindered creativity flow and iterations. It also added cost and administration to the development process. All in all decreasing their efficiency. Instead, they chose to invest in a machine which (for their needs) could be used both in prototyping and end use parts, the Dimension SST 1200es using FDM technology. Koenigsegg is using the Dimension system to print everything from engine parts to tooling and fixtures. Components can be printed to test mountability and serviceability. [54].

> *"The process of printing prototypes onsite and testing each component has sped up the development of the car design by an estimated 20%."* [54].

Koenigsegg has also used metal AM in direct part production for their new model One:1, namely a turbo housing (see figure 3.7) and a tip of an exhaust system (see figure 3.8).

When designing the turbo housing for the One:1 attempts were made to manufacture it by the conventional method, casting. With additional iterations on the design it might have been possible. Though as a small series manufacturer they decided it would be more cost effective and easier to use AM with stainless steel for this task successfully. As there was no longer any need for a tooling or development thereof, they saved both money and time. As they also incorporated moving parts in the print they avoided issues with fitting of the components and lowered the cost for assembly. [55].

Figure 3.7 Koenigsegg’s variable geometry turbo fabricated through AM. Seen to the right. [56].

Their tip of the exhaust system for the One:1 is allegedly the largest piece ever printed in titanium. It takes three days to manufacture. [57].

Figure 3.8 Koenigsegg’s tip of their exhaust system [58]. Post processing was most likely required for the glossy finish.

3.2.1.10 Lamborghini (Part of the Volkswagen Group)

The use of AM has accelerated Lamborghini's prototyping by reducing cost and improving the workflow efficiency. Previously the prototypes were outsourced, but in 2007 it was brought in-house as a Dimension 1200es FDM machine was installed. In 2010 yet another FDM machine was installed, this time a Fortus 360mc which was followed by a Fortus 400mc in 2013. [59].

> *"*[Lamborghini uses AM most frequently in] *scale models and advanced functional prototype parts for design verification and fit and form suitability. These include an array of different exterior parts – from section bumpers, grills, aesthetic frames and those in the engine bay – to various interior parts that span door panels, seat covers and steering wheels, along with aerodynamic components such as conveyors and air heaters."* [59].

Lamborghini is also using the FDM technology for their motorsport program. They are reportedly using ULTEM 9085 for some parts requiring high strength and toughness (when compared to other plastics). See figure 3.9. [59].

Figure 3.9 Air aspiration engine conduit and elbow support door panel, produced in ULTEM 9085 on a Fortus 400mc [59].

When developing their latest model, the Aventador, many prototypes were used to *"*validate assembly fit, verify efficient load paths, and identify and correct issues that were invisible on the computer screen" [60].

> *"We had to get the design right the first time because the tooling used to produce just the monocoque cost several million dollars."* [60].

When using traditional methods, the building of a scale 1/6 prototype monocoque would consist of making scaled tooling and then build the prototype out of carbon fibre reinforced plastic, CFRP. This is a very costly and time-consuming process. Using an AM machine instead with FDM technology, Lamborghini saved on both lead-time and cost. The build time in the AM machine was 6.3 days and if including the post processing it took 20 days in total. See table 3.3 for the comparison. [60].

Table 3.2 Comparing traditional process and the AM alternative for the 1/6 scale model [60].

Method	***Cost***	***Lead-time***
Traditional process	$40,000	120 days
FDM technology	$3,090	20 days
Savings	$36,910 (92%)	100 days (80%)

3.2.1.11 Mercedes

For the next generation of their S-class, believed to go on sale in 2018, Mercedes has been looking at implementing additively manufactured parts. When asked if "the one-piece air vents and other intricate details like the speaker grilles could be 3D-printed, making them stiffer, lighter and faster to manufacture?" The answer from Jan Kaul, Mercedes chief interior designer was *"Yes, for sure. But this is a question of margins. We must be making thousands of these components to be sure the quality and cost is viable."* [61].

3.2.1.12 Peugeot

For the 2015 Frankfurt International Motor show, Peugeot built a concept car showcasing components made with AM. The Peugeot Fractal is built with a state-of-the-art sound system and with an interior trim designed to enhance the sound experience for the passengers. The interior consist of several printed blocks, covering up to 80% of the Fractal's interior, and is used on the cars "floor, sides, and door panels". The design has taken inspiration from recording studios where the sound is of great importance. See figure 3.10. [62].

Peugeot's Strategy Director Jerome Micheron claims that without AM, the building of the intricate interior for the Fractal would not have been possible. Peugeot also believes that with the help of AM, they can make a "finer design that is both lighter and more efficient than today's industry standard". [62].

Figure 3.10 Interior of Peugeot's concept car Fractal. [62]

3.2.1.13 Volkswagen (Part of the Volkswagen Group)

With the development of the new generation Golf, Volkswagen (VW) took help from the tooling and prototyping firm Robert Hofmann GmbH. While preparing the series production of a new model, companies are always striving for lower cost and shorter lead-times. During this time concept cars and pre-series production cars are built and the parts are changed as they are tested during the development. Because of this progression, Hofmann faced the challenge to provide several individual parts for concept cars, plus preparing up to 100 prototypes and also the 50 to 100 pre-series production cars that are built. To meet the different demands in the three phases, the personnel at Hofmann used different strategies, such as "moulding processes, rapid prototyping technologies and highly specialised finishing techniques". For the Golf VII program, there was a need for AM both in prototyping and in production, with batches between 100 to 120 parts for small series limited production. [63].

> *"Having one supplier for prototypes and series production tooling enhances quality and improves meeting the project's lead time challenges. The customer gains valuable input through our model building expertise during the development phase. Our tool-making service seamlessly bridges the gap from the development prototyping phase to the series production personnel at Volkswagen."* [63].

For the VW Golf mark VII, Hofmann supplied VW with 30 injection moulding tools with a lead-time of 10 weeks. Once the design was approved by VW, Hofmann starts with the production of the moulds "for individual components including halogen headlights, fog lights, reflectors, rear lights, boot door covers, side panels for seat covers and the dashboard". They are using metal AM machines from

Concept Laser, however they do not say precisely what they use them for, if it is for tooling inserts, the tooling, prototyping or direct part production for the end product – perhaps it is all of these areas. [63].

A component that probably is manufactured with AM was shortly displayed in one video from VW, see figure 3.11. It is part of their fix for the affected engines in the Dieselgate scandal. The prominent stepping effect seen on the surface is most likely the cause of an AM process as it is a very characteristic outcome for many of the processes. Although it is unlikely that VW will print these directly to the customer due to the large quantity needed, [64] speculates on some opportunities and strengths if VW would go for this alternative. More specifically, if they choose to install AM at each dealership to print onsite.

> *"The benefits of better, faster innovation and a digital supply chain would be a huge advantage for Volkswagen. Their speed-to-market would be unmatched. But beyond that, the transparency inherent in a digital solution would certainly help demonstrate the company's commitment to open innovation as a means of resolving big problems."* [64].

With easier distribution, iterations of design could be sent digitally, printed locally and installed in a vehicle just-in-time. It could even open up for new business at the dealerships, accessorising for example and customer involvement in design. Ultimately, what [64] proposes is a way of revitalising the VW brand while possibly also setting up for a competitive advantage in the future with a wide network of printers around the world. It might be expensive, but the alternative is also expensive and the other values it might bring with it might overweigh the cost.

Figure 3.11 The flow transformer, most likely printed. It is unclear from the source if this is just the prototype or if this is for the actual end part. [64].

3.2.1.14 Divergent Microfactories

Divergent Microfactories aims to be an eco-sustainable supercar. By reducing weight, fuel consumption and wear on roads are minimised. But a large portion of the ecological footprint also exists in the manufacturing phase.

> *"Society has made great strides in its awareness and adoption of cleaner and greener cars. The problem is that while these cars do now exist, the actual manufacturing of them is anything but environmentally friendly, we've found a way to make automobiles that hold the promise of radically reducing the resource use and pollution generated by manufacturing."* [65].

Their solution is to have a modular system using a space frame consisting of nodes manufactured in metal AM and carbon fibre tubes, see figure 3.12. They achieved a weight reduction of 90% of the chassis by better material utilisation while still fulfilling the structural needs. Their vision is that there will be micro factories all around the world, fabricating their car locally to further reduce the footprint.

Figure 3.12 A space frame built out of printed nodes and carbon fibre tubes [66].

3.2.2 Motorsport

3.2.2.1 Bloodhound SSC (Supersonic Car)

With a goal of reaching 1,000 miles per hour (1,609 km/h), the Bloodhound SSC will make an attempt on the world speed record for the fastest car on land to date. As part of this effort, a functional prototype of the nose tip was fabricated through AM with the help of the service bureau Renishaw using titanium in their machine AM250, which is a powder bed fusion process. [67]. Although they do not state clearly, it seems likely that the end use part also will be printed directly as they are talking about having a complex shape to optimise for low weight.

At these speeds the parts of the car have to withstand extreme conditions, and to achieve their goal optimising weight and distribution thereof is crucial. Perhaps that is why titanium, both lightweight and strong, will be used for the nose tip.

> *"We believe that the key benefit of using an additive manufacturing process to produce the nose tip is the ability to create a hollow, but highly rigid titanium structure, and to vary the wall thickness of the tip to minimise weight. To machine this component conventionally would be extremely challenging, result in design compromises and waste as much as 95% of the expensive raw material."* [67].

In their video they show another titanium printed part, see figure 3.13. Although it is simple in shape it might be both much more environmentally friendly and more economical sound than milling it from one block of material. When considering the whole life cycle of a product, from mining the material to the disposal, AM might be a much better alternative if there is a lot of scrap in a process. It is extra clear when it comes to titanium, as it is so expensive. [67].

Figure 3.13 A component printed in titanium. Simple in geometry but it still might be worth printing due to environmental and economic aspects in the alternative of milling were 9/10 becomes scrap. [67].

3.2.2.2 Lotus F1 Team

Lotus F1 team begun using AM in 1998, at the time under the name Benetton. The first machine was the SLA 5000 from 3D systems. It was mainly used for producing prototypes, and its main application were testing function and fit. Eventually the potentials in rapid iterations became clear. For aerodynamic purposes they could now test hundreds of prototypes per month. [68].

> *"In Wind Tunnel testing, aerodynamics is an empirical science. We design and compare new ideas and choose directions to follow. The more ideas we can compare and evaluate, the more successful we will be on the track.* […] *The car model in the wind tunnel features a complex network of pressure sensors. These were positioned by drilling pressure tappings into metal and carbon fiber components before SLA technologies became available. The ability to produce complex solids with intricate internal channels has revolutionized our ability to place these sensors and increase their numbers. It's a dream come true for aerodynamicists!"* [68].

Since then they have launched an AM centre in 2002 with even more machines, including “five SLA iPro 8000 Systems, one SLA 7000, one Sinterstation Pro 140 SLS System and two Sinterstation HiQ SLS Systems”. They report that each year they have used an increasing number of components fabricated in SLS machines in the actual F1 car. [68].

The gearbox and suspension are two components in which Lotus are using AM. Casting patterns for these are made out of plastic AM with SLA machines. A greater design freedom can be gained with AM than conventionally made patterns, allowing the engineers to be more innovative with their designs. As the SLA process is accurate enough for this, less time have to be spent on proof machining the component afterwards. [68].

The ultimate goal however is to use AM as a fully industrialised manufacturing method and thereby “reduce cycle time and cost” [68]. The technology is not quite there yet with some issues which still needs to be resolved. In attempt to get closer to industrialising AM the aerospace company Boeing has teamed up with Lotus – both needing low weight and high performance parts. While Lotus have a much quicker turnaround time allowing for more testing, Boeing is not as agile. [68; 31].

Together, the Lotus F1 team and Boeing developed a new AM technology to achieve better uniformity throughout the layers which otherwise could be problematic with AM. The layer by layer process used by AM usually “leaves room for structural errors, as not all layers will have the same strength, stiffness, and all-around structural properties”. The solution they came up with utilised recycled carbon fibre reinforced plastic in a SLS process, fusing particles and fibres of carbon together with plastics. The fibres are randomly distributed through the cross section and the particles fill up the cavities resulting in a high uniformity of the mechanical performance in all the directions. Before they came up with this solution they also considered; reinforcing plastics in a usual SLS process as it would benefit the overall strength but still suffer from the low uniformity in mechanical properties; and adding a more advanced feedback system for the parameter control of the machine which was ruled out as it requires a lot of research and the likely high cost of the added complexity needed in the machine. [31].

3.3 Aerospace

Using AM for prototyping is a well-established practice within the aerospace industry but it is only in recent years that AM has taken the step into production of end use parts. Likely much to do with the high requirements needed for approval. While companies like General Electric are working on attaining flight approval for metal printed parts, Stratasys is working on their plastic materials. [69].

Just as within the motor sport industry there is a constant search for ways to make the end product lighter. This could save substantial amounts of fuel consumption during the life span and thereby reducing costs and carbon footprint.

Compared to the automotive sector, the barrier for entry is higher within aerospace meaning that they are less threatened by competitors and therefore more likely to showcase their usage of AM.

3.3.1 Airbus

On May the 6th 2015, Stratasys announced that Airbus has used AM in over 1,000 parts for their passenger aircraft A350 XWB in a press release. Stratasys stated that Airbus used AM for its flexibility, making it possible to meet their delivery schedule. The parts were made with Stratasys FDM technology in ULTEM 9085, a plastic which meets Airbus needs and also the "flame, smoke, and toxicity (FST) requirements for use inside of an aircraft". [69].

> *"Our additive manufacturing solutions can produce complex parts on-demand, ensuring on time delivery while streamlining supply chains. Additive manufacturing also greatly improves the buy-to-fly ratio as significantly less material is wasted than with conventional manufacturing methods. Stratasys is looking forward to bringing these and other advantages to its collaboration with Airbus."* [69].

Not only plastic parts are being implemented in Airbus aircrafts. The new jetliner A320neo will have borescope bosses (see figure 3.14) fabricated in nickel alloy using AM, which previously were machined. The new bosses will instead be directly fabricated in an AM powder bed process, using a machine from EOS. This allows for a reduced cost both in development and manufacturing, and a greater design freedom. With this and some other upgrades, the aim is also to reduce fuel consumption by 15%. [70].

Figure 3.14 Borescope boss made with AM for the PW100G-JM GTF engine. [70].

There are plans of producing 2,000 bosses each year and 16 within a single print. Together with EOS, MTU is working on optimising their AM methods. Some of the goals are better surface finish, integration of MTU's own raw material with the help of a new process chain, implementation of "new online monitoring and quality assurance systems" allowing MTU to monitor the prints layer by layer. [70].

> *"About ten years ago, we began using AM to produce tools and development components. To optimize utilization of the capacity, we went in search of further areas where we could apply the technology. The borescope bosses for the low-pressure turbines of the A320neo's GTF engine were ideal for AM.* […] *They are small components riveted to the turbine housing that create openings to allow technicians to check the condition of turbine blades inside the engine. We see a lot of potential for the manufacture of further series components for aero engine construction, such as bearing housings and turbine airfoils, both of which need to meet the highest demands in terms of safety and reliability."* [70].

The Airbus division Defence and Space is also using AM. Under two years, they have been involved in a R&D project (with focus on objects that cannot be fabricated in other ways) which now (2015, March) have enabled them to print their first space qualified aluminium components. One component they have been using this for is the structural bracket for telecommunications, see figure 3.15, which requires high stiffness to provide greater accuracy for the antennas that will be mounted to it. By printing the bracket instead of conventional manufacturing, they were able to make a 40% stiffer structure, decrease weight by 35% and consolidate 48 individual pieces into one (and thereby also eliminating assembly of these). [71].

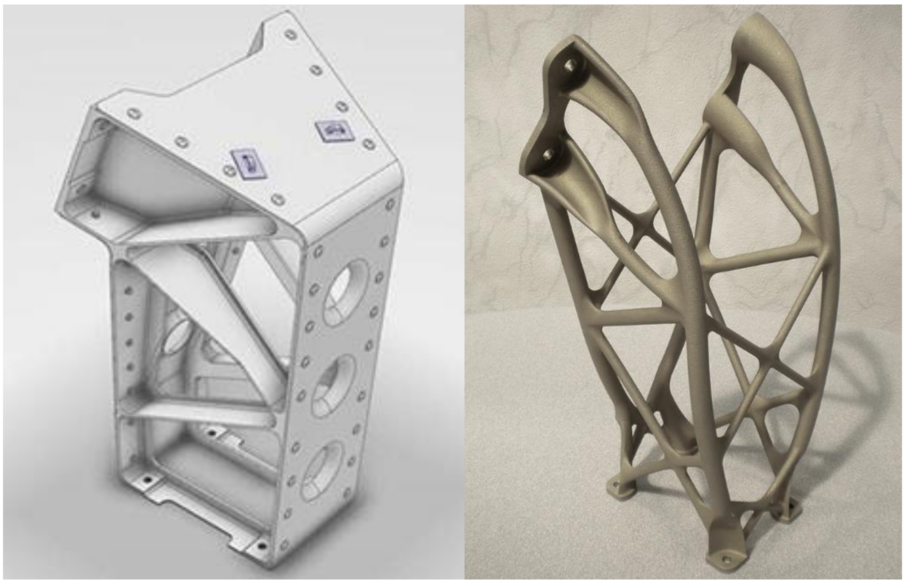


Figure 3.15 A comparison of the old and the new bracket (which cannot be manufactured conventionally) [71].

3.3.2 European Space Agency, ESA

ESA has collaborated with the AM machine manufacturer 3D Systems on metal AM to find out how useful it is for ESA's needs. In this quest, the conventional design of their injector, combustion chamber and expansion nozzle have been printed – using 3D Systems' DMP technology. They have also investigated benefits of redesigning the components for AM. [72]. See figure 3.16.

The flow in the injector could be optimised and made into one component instead of five. The combustion chamber also benefited by part consolidation and as they use a micro lattice structure, weight could be reduced and or structural safety margins increased, see figure 3.17. The expansion nozzle benefited most from the potential AM gives in customisation. More tests needed to be carried out to see if the requirements were met. [72].

> *"By acquiring full control over the AM production process, 3D Systems achieves a homogeneous micro structure with a relative density of up to 99.98%, for an increasing number of metal and alloys including titanium."* [71].

Figure 3.16 Satellite engine injector, combustion chamber and large-scale expansion nozzle all directly fabricated with titanium AM using 3D Systems' DMP technology [72].

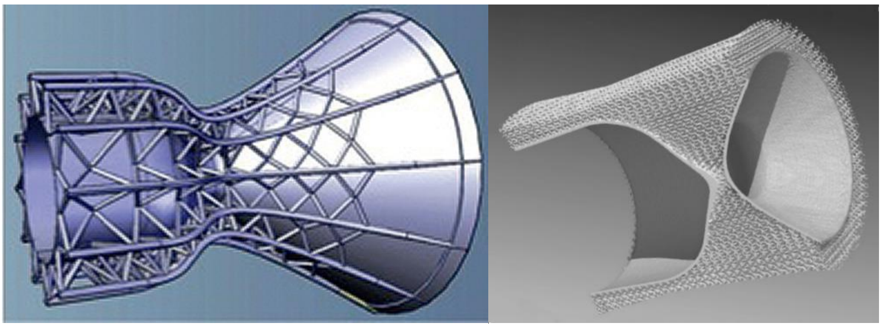


Figure 3.17 The conventional and part of the redesigned combustion chamber in figure 3.16 [72].

3.3.3 General Electric, GE

GE works with both developing components both for new generations of jet engines and retro fitting old ones with solutions that is not possible with any other means than through AM. They were also the first to get “3D-printed part certified by the U.S. Federal Aviation Administration (FAA) to fly inside GE commercial jet engines”. [73]. And as they are building AM plants across the world and even a plant for mass production in metal AM they are most likely seeing enough profit and potential in using AM.

GE has invested over $1 billion on research to improve their fuel nozzles, using the design advantage of AM. GE has completely redesigned their fuel nozzle for AM for their LEAP jet engines. As 21 parts were consolidated into one complex version a much higher design freedom was gained. This enabled an optimisation, better utilisation of material and function, which in turn contributed to a considerable reduction of fuel consumption while also gaining a higher thrust and five times the durability. [74]. See figure 3.18. New nozzles are being developed for the GE9X engine and Boeing’s 777X, and testing for the new generation of LEAP engines are ongoing. [75].

To mass produce the nozzles, a $50 million plant was opened during 2015 in Auburn, Alabama. So far 8,500 LEAP engines have been ordered, and with 20 fuel nozzles needed per jet engine means the quantity will be at least 134,000. [74].

Figure 3.18 Additively manufactured fuel nozzle [74].

For Boeings new long haul 777 liners, GE is developing the world’s largest jet engine, GE9x with AM parts. Compared to the GE90-115B engine, which is used on the existing Boeing 777-300ER liners, the new engine is “expected to deliver

100,000 pounds of thrust while reducing fuel consumption by 10 percent". To achieve this, GE's engineers and technicians used AM extensively in the prototyping phase, making sure that any simulation of their new composite turbine that resulted in fuel consumption savings under 10% were quickly modified. The weight of the engine itself has also been reduced, thanks to new materials and AM technologies. [74].

3.3.4 Rolls Royce

During 2015 Rolls Royce will allegedly flight-tested their Trent XWB-97 engine for the first time, equipped with a front bearing housing containing 48 aerofoils fabricated through AM. With a diameter of 1.5 meter and 0.5 meter deep, it is said to be the largest part that ever been built with AM in titanium. [76].

Rolls Royce has previously tested several engines on the ground containing the AM bearing housing, but no engine equipped with such a large AM part has ever been used in flight to power an aircraft before. Even if the production engines will not be using the AM bearing housing, at least not in the beginning, but Rolls Royce claims that the project "is a key step towards proving the industrial viability of the process" which could reduce lead-time in manufacturing with up to 30%. Rolls Royce do not however want set a timeframe for when to implement AM for industrial use for components of this scale. "We have a lot of work to do on scalability before making a commitment to production." They have for at least five years built a knowledge base on fabrication with metal AM by doing case studies on repairing components. [76].

The barriers for use in prototypes however are recognised as lower because of the reduced lead-time and cost in development.

> *"It is ideal for prototyping. Shortening the manufacturing time by almost a third gives us more time to design, which is always a benefit. We are also able to produce designs that we wouldn't otherwise be able to do."* [76].

3.4 Tooling

3.4.1 Injection Moulding

3.4.1.1 Whale Pumps

In a quest to reduce the time to market for their products, open up for innovative solutions, and speed up their R&D, Whale Pumps studied how AM could benefit them. Whale Pumps designs and manufactures "a diverse range of pumping and heating systems that include plastic and rubber parts for consumer and industrial applications around the world". These parts are produced in-house, with Whale Pumps own injection moulding system. The tooling used in this process are not only costly, they require CNC machining and takes more than a month to produce. And adding to this lead-time, they usually outsource their functional prototype parts to China. [77].

They decided to invest in a PolyJet printer from Stratasys and a few months later they bought another one as well. The R&D engineers quickly started producing prototypes. They were a bit hesitant to use it for injection moulding though and worked with Stratasys to develop a new material a bit more suitable to higher temperatures and pressures, resulting in the Digital ABS material. This allows Whale Pumps to manufacture the tooling in-house quickly and at a very low cost compared to the metal tools. [77]. It is probably not as durable as metal versions though.

> *"With our Stratasys 3D Printer, we are now able to design our tools during the day, 3D print them overnight and test them the next morning using a range of end-product materials. The resulting time and cost savings are game changers for our business."* [77].

3.4.1.2 Innomia

Magna, customer to Innomia had a problem with the tooling for a central arm-rest. The arm-rest is made of a glass fibre reinforced plastic, produced with injection moulding. The problem arose from the design of arm-rest, as with conventional manufacturing methods the tooling could only be made with cooling coming from one side – the tooling has an uneven temperature distribution leading to high cycle times and deformations. To solve the problems, a tool insert was made out of beryllium-copper, a material with excellent heat-conducting properties and to absorb the heat from the molten plastic, the cooling water has a temperature of just 16°C and the insert surface get as hot as 120°C which led to humidity problems with accelerated corrosion as a result. This meant that a "cost intensive cleaning being necessary every one to two weeks". [78].

The engineers at Innomia quickly saw that cooling was the main issue, and set about to develop tooling where heat removal was the main priority. With the use of AM, the engineers have been able to design a new path for the cooling channels, leading to a more uniform heat distribution and dissipation. [78].

> *"The DMLS process, using the EOSINT M 270, enabled us to manufacture an extremely durable component, while at the same time successfully retaining the proven advantages of the method in terms of design and reduced cycle times. Thanks to the cooling channels, integrated in the component with optimum precision, we have resolved the main challenge of the production process, and done so with limited expense."* [78].

With the new cooling channels, the temperature difference between the cooling water and the tooling surface have been reduced dramatically, solving the issue of humidity and corrosion. Maintenance interval was as a result reduced from five to six weeks. And because of the much improved cooling channels, the time for the production cycle got improved with 17%. During operation with the new AM tooling, Magna and Innomia have been able to further improve the process parameters and after 370,000 cycles Magna has saved 20,000 euros compared to the old tooling. [78].

> *"The issue of cooling was something that we've been trying to deal with for a long time. We knew how an improved product would have to look, but manufacturing it just wasn't possible. Additive Manufacturing allowed us to make the breakthrough. We were able to plan the cooling channels just as we wanted them and then manufacture the mould core correspondingly. The laser fuses the metallic powder layer by layer, so that in effect any shape is possible. The result has convinced us at every level. Maintenance, quality of the end product, costs, heat dissipation – it's been the perfect project."* [78].

3.4.2 Thermoforming

3.4.2.1 Xerox

For the last two and a half years, Xerox has used FDM for the production of thermoforming moulds used for the production of packages for their products. The FDM machine was used for prototyping at first, but the application extended to also include "fixtures and assembly tooling for use in its manufacturing processes". [79].

> *"When I was chatting with a Stratasys application engineer, he mentioned that it's not difficult to produce an FDM part with an air gap. That gave me the idea of using a porous FDM part as a thermoforming mould. I worked with Stratasys to set up the machine correctly. It took a bit of experimentation to get just the right porosity to draw the vacuum needed to mould the part."* [79].

Previously, Xerox used CNC wood moulds that cost around $1,200, taking a week to produce. With FDM the moulds are made within hours, with cost as low as 10% compared to the wooden ones. "The more expensive it is to produce the mould, the more apt you are to settle for less than optimal results." By using a porous mould, instead of the wooden ones, that uses drilled holes for the vacuum, results in a more uniform vacuum leading to better component quality. With the use of AM, geometric limitations from the machining process does not need to be accounted for, which often leads to improved mould performance and lower component cost. The speed and low cost of AM moulds also opens up for the engineers to make more iterations, further improving the performance and cost. [79].

3.5 Lessons Learned

See table 3.4 for the lessons learned in the benchmark.

Table 3.3 Lessons learned in benchmark.

	Lessons learned
7 AM categories	The components displayed in this benchmark are ranging from high performance parts to functional prototypes to prototypes in the lower end. As stated in the introduction to the benchmark it is problematic as the outcome will depend on the specific machine and settings thereof, a better knowledge gathering for the maturity would probably be per machine. A new machine was found during the benchmark study, namely the technology that Boeing and Lotus have developed together.
Application areas	The use of AM stretches through the various phases of development in both direct part production and tooling. Using AM for prototyping seems to be the most common practice in AM among the companies in this benchmark. From their statements it seems to be a growing interest for using AM in production. Some were already using it for manufacturing aids and tooling. Some even use it to directly fabricate the end product, though from the information in this benchmark only the aerospace and motorsport industries have made public statements on this. GE has even started plants for mass production.
Design methodology	The information on design methodology for production purposes was limited in the findings of the benchmark. One example though is BMW's use of 3D-scanners to customise manufacturing aids with AM for their employees.
Implementation of AM	For niche areas it seems to be viable to use AM in production today.

3.6 Future Work

The benchmark presented here is just a selection on the known information within the automotive and aerospace industries and the use of tooling in other industries. There are more industries and areas that could be examined, jewellery and medicine for instance. Especially the medicine sector might be interesting as it is said to be leading the technology development forward [80].

Benchmark on AM easily gets dated, therefore it needs to be updated every now and then to not miss out on new opportunities and to keep track of competitors.

4 Application Areas

The value gained from AM has to be evaluated in the light of what it will be used for. What are the alternatives and how do they compare to using AM technology? Answering these questions would help in deciding whether or not it is worth looking into AM in the first place for the specific project. As a first step, this chapter therefore explores in which ways AM can add value.

"The value of an idea lies in the using of it." – Thomas Edison.

4.1 Introduction

As seen in the benchmark, the opportunities of AM are huge and multifaceted. When just looking at what others have done you might get some inspiration of what you might do, either directly in fabricating the same components or indirectly by getting inspired by it. To navigate within the possibilities AM enables and to truly find novel uses of the technology, examining the benefits that AM enables in a more theoretical perspective might prove valuable. It will always be in relation to the alternative solution and to the requirements of the specific project. Therefore it is up to the reader to judge from their specific needs whether AM is a good choice and also evaluate if it is a feasible alternative.

4.1.1 Value Theory

With products and services, value is created, delivered and captured. Value could be created either by creating a value to the customer that is higher than the cost of producing the product or service, or by discontinue if the cost turned out to be higher than the created customer value. Value is then delivered through the organisation's capabilities in creating the new product or service and in the customer's choice to actually make the purchase. It is possible though to affect the customer in the decision making through marketing, sales approach and support. When the value has been created and delivered, some of the value can then be captured through the company's revenue model. [81].

Customer value is subjective. According to [82], the created customer value could be derived as the customer's desire in a product or service before the purchase has been made and the customer’s perception of it afterwards. In the automotive industry customers are more affected by their sentiments of a product than the technical functionality [83]. The perception of the value is at different levels. At a basic level of needs were it needs to fulfil the customer’s perceived wants of the product or the service. On the higher self-actualisation level it might have the influence to give an emotional satisfaction as well as the possibility to achieve goals or desires through the product or service. The customer value will be in proportion to what he or she had to sacrifice in the purchase, e.g. money and time. [82].

It is not only the customer who are affected by an organisation’s value creation but all the stakeholders [84]. Reversely, a company has a moral and ethical responsibility to do right by these. Nevertheless, it is usually a compromise and as such it is up to debate who the most important stakeholder is. Who the stakeholders are will depend on the specific project. Some examples are the driver, the passenger, the owner, the buyer, the investor, the employee and the society as a whole. With the current environmental crisis perhaps the most important stakeholder is the society, were the environmental aspects of AM and its usages should be closely analysed to minimise the overall impact. [85].

4.1.2 Some AM Enablers and Barriers

AM enables new opportunities in adding value, it could be through inventions and optimisations in current designs, but it could also be in improving the process of developing products, in manufacturing, or even in the services to the customer – as you will see in this chapter. Depending on the usage it could possibly reduce cost and or create a value to the customer that could motivate a higher price tag.

The enablers of AM all seems to originate from its tooling-free-nature. Without the constraints of tooling a higher design freedom is gained. The part could be manufactured just-in-time and to the specified quantity without reorganising the production site or much preparation other than sending the CAD-file, provided that a suitable AM machine is available.

Especially interesting is the greater design freedom, see figure 4.1. The higher complexity of a component the more inconvenient and costly it is to manufacture conventionally, no matter if it is a formative or subtractive manufacturing method. For subtractive manufacturing such as milling, the complexity will be greatly limited by the used tools and the limitations in the machine. For formative processes, such as injection moulding and casting, it is necessary to develop and produce tooling. If the tooling is based on subtractive manufacturing the complexity will as previously mentioned depend on the used tools and machine, additionally it has to take process related constraints into consideration, such as draft angles so that the manufactured part could be released from the tooling. Conventionally manufactured parts might therefore reach a point where it no longer is cost effective relatively to AM, or it might even be impossible to manufacture by any other means than AM.

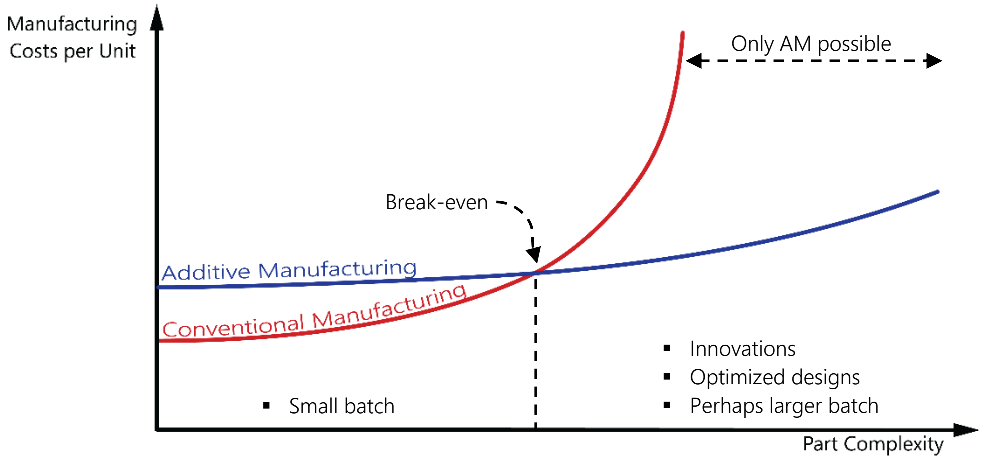


Figure 4.1 Rough sketch on the correlation between part complexity and cost per unit when mass produced. Based on [86].

As mentioned in the introduction, there are barriers especially for mass production, such as low speed, high cost of materials and machines, need of post processing, and or lack of quality. With the low capital investment needed of AM, it could then be derived as a technology ideal for the economy of the few were many diverse components in the smaller batch could fill up the capacity of a machine. With the slow process it is generally more profitable when the components are small. Using the inherent capabilities of AM such as the complexity advantage could perhaps provide value that would outweigh the cost even for the larger batches and the bigger components. [87]. Although, to tell for sure whether or not a part ought to be manufactured through AM should be evaluated from case to case.

4.2 AM in Modelling and Prototyping

Historically, AM has thrived as a method in modelling and prototyping. This usage is also referred to as *rapid prototyping* (RP) [5, p. 2], The tooling free nature of AM makes it ideal to cost efficiently and rapidly produce the small batch and the frequently changing design that modelling and prototyping usually are characterised by. And because of AM, more iterations could be made with the same funds and within the same time frame or less – making it possible for earlier entry to market and or bringing a more refined product to market.

There are more benefits that could be derived for rapid prototyping such as communicating ideas, fostering creativity, temporary part consolidation[8], etc. The value gained is hard to define and predict. It would involve; defining the specific use of the modelling or prototyping; answering how much time is worth; predicting the market; anticipating the value of a design invention or improvement; etc.

> *"Everybody wants to know how much 3D printing has saved in dollars, but when you're talking prototypes, it's time. What would bringing a product to market a month early do for you? That's millions of dollars. It's not something that's easily measured." – Harold Sears, a technical specialist at Ford.* [44].

From a proof of concept perspective, the optimal prototype is produced the same way and made out of the same material as the final product in order to discover unforeseen design flaws early on [88]. As the degree of product maturity increases the design gets gradually more fixed. The cost to do changes in hindsight increases significantly as investments and decisions ties up the leeway. [89, p. 6]. If the design has to be revisited, the later in a project the more costly it usually is. Investment in tools and tooling might already been made, one change in one component might affect others in a system of components meaning that they also have to be redesigned, the time to market might be affected, etc. [90] See figure 4.2.

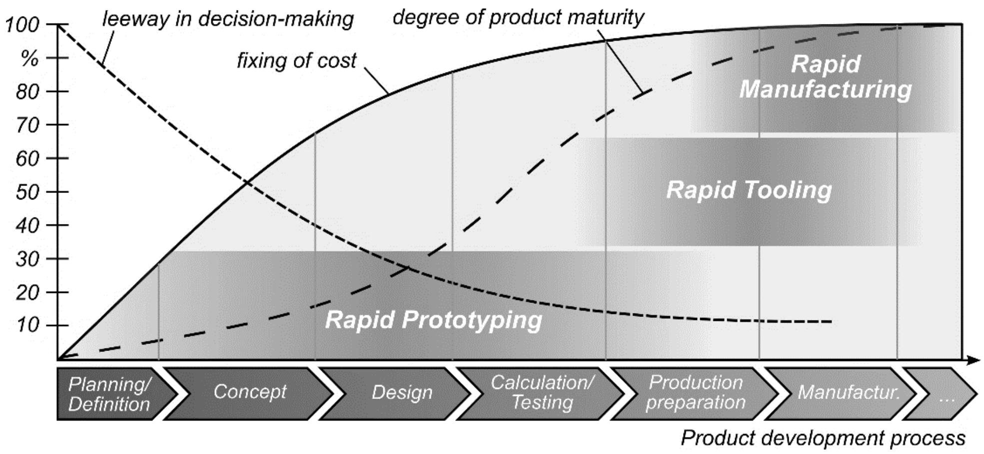


Figure 4.2 A rough model on the usage of additive manufacturing[9] in the product development. The gradients indicates that the timing is dependent on the specific product. Image courtesy of Prof. Dr.-Ing. Stéphane Danjou. [89, p. 6].

---

[8] Temporary part consolidation refers in this thesis to printing several parts in one piece for modelling and prototyping purposes. It will however be in several pieces when it will be manufactured later on. It might be possible to do part integration even for the end product if it is manufactured using AM.

[9] Additive manufacturing includes rapid prototyping, rapid tooling and rapid manufacturing.

4.3 AM in Tools, Tooling and End Products

Additive manufacturing could be represented in almost every phase of the product development process [89, p. 6]. Apart from modelling and prototyping, the tools and tooling or even the end product could be produced directly through AM. These uses are referred to as *rapid tooling* (RT) [5, p. 2] and *rapid manufacturing* (RM) respectively. See figure 4.3 for the relation between RP, RT and RM.

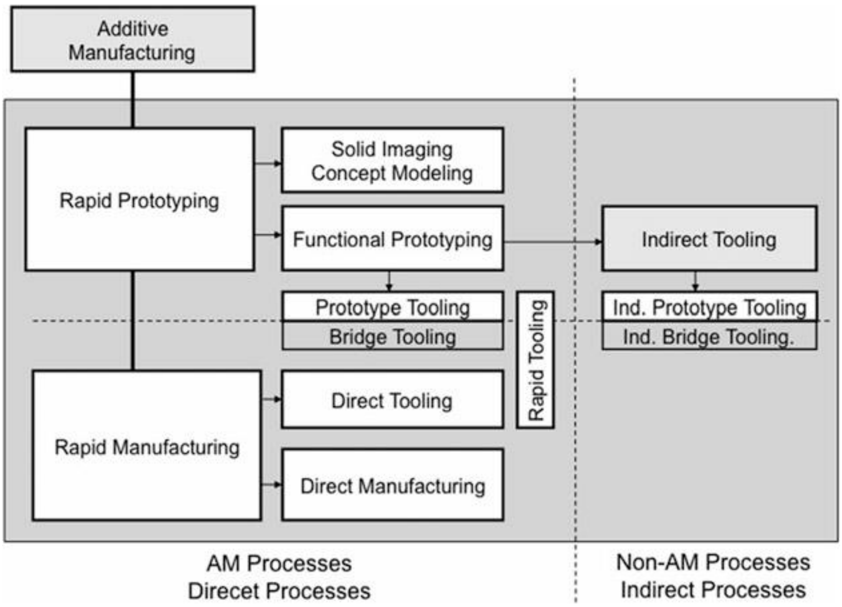


Figure 4.3 Correlation between RT, RP and RM. Image courtesy from Springer Science and Bus Media B V [91].

To thoroughly investigate what the value of using AM in production could be; cost reduction/increase should be evaluated with RT and RM respectively and compared to its alternative for the specific product; reduction/increase in lead-time should be estimated; and predicting the customer value of an invention or redesign using RT or RM could provide.

Books could be, and have been, filled with information on RT alone discussing; the possible outcome in durability, tolerances, surface finish, lead-time savings, etc.; how traditional tooling could be enhanced; the new types of tools and tooling enabled by RT; etc. However for this paper there was no time to go into great detail for the various tooling. Some tips on literature for the interested readers; in 2004 an insightful review on rapid investment casting methods with RT was published [92]; in 2009 a book on RT and industrial applications was published [93]; in 2010 a book on guidelines and various practises for sand casting was published [94]; and more recently, in 2016 a short article was published on injection moulding [95].

Both tools and tooling contribute in the fabrication of the end product. If the end product is printed directly though, it could entirely or partly replace tools and tooling. One approach of dividing the coming text could be just that, RT and RM. From a value perspective though it should be noted that; the design advantages AM enables allows for new innovations and design improvements in end product towards customer but AM could advantageously be used for a conventional design as well; tools and tooling could be disposable [10] meaning that getting some complexity in the end product is possible even with RT; and that manufacturing aids are a separate business case entirely as it does not necessarily affect the product to the customer notably.

It might be more expensive to print a conventional design over a design optimised for AM because; a conventional design might not be as efficient in material utilisation, see figure 4.4; and a conventional design in some instances might be trickier to print. It is also a question of how large the production volume will be and if the AM printed part will be a direct cost for each end product or an overhead.

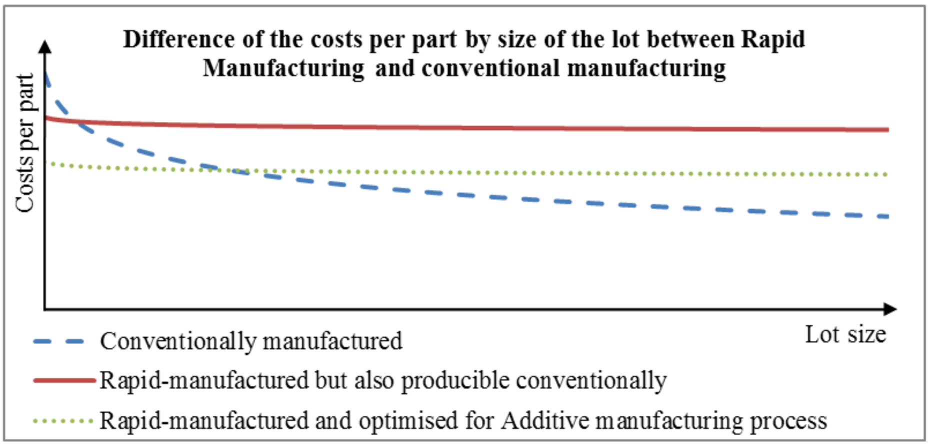


Figure 4.4 Cost and production volume dependency in conventionally manufacturing (i.e. formative manufacturing), RM with a conventional design and RM with design optimised for AM. Image courtesy of Florian Weiss, IKTD, University of Stuttgart. [96, p. 3].

With the heritage AM has in RP, there exists a mental barrier for the adoption in production with the belief that it is not quite ready for production purposes [6, pp. 98-99]. And it is partly right, not all machines and materials are suitable for production and the possible result will depend on many factors. Moreover it has to be evaluated from case to case if the production method can meet the requirements of the end product and production volume, and it might even have to be evaluated from time to time as AM seems to be constantly evolving.

---

[10] Some types of tooling are intended to be destroyed after the part has been formed, such as lost wax casting, investment casting and sand casting.

4.3.1 End Products with Conventional Design

AM could be used advantageously with RT and RM both, even if the end result is a conventional design intended for other manufacturing methods, i.e. formative and subtractive methods. The possibility to change to another manufacturing method without having to redesign remains with a conventional design.

In the lower series there could be economic viability in using RM, see figure 4.4. Such as; a first step for testing markets; in low series of vehicles; late changes before the tools and tooling has been developed and produced, see figure 4.2; in so called bottle neck areas were the available capacity is low; and in the supply chain were the demand is limited and localised [97, pp. 3-4].

Using RM in mass production with a conventional design in the end product might not be ideal as it probably would be quicker and more cost effective to produce with other methods. Paying more for AM without using its inherent capabilities for mass production is unwise unless there are no time for producing the tools and tooling or lack of needed capital investment. [87].

RT is another business case entirely as it could be shared by a larger quantity than one. Naturally, the end product with RT still has to take manufacturing constraints such as draft angles into consideration. Tooling could be printed to fabricate end products directly or indirectly when printing patterns that is used in a secondary process to fabricate the tooling. The tools and tooling could benefit from the complexity AM enables. Injection moulding for example could in theory be enhanced by optimising the cooling channels and thereby increase production speed, easier eliminate the risk of defects, and perhaps not needing as many tooling to reach the target production speed and quantity [95].

4.3.2 End Products with AM Design Advantage

AM could also be used advantageously, both with RT and RM, if the end product has a design which is inconvenient or even impossible to manufacture in other ways. See figure 4.2.

When using the design advantages in the end product new designs and inventions are enabled. This means that products could be truly optimised for functionality. Parts could be consolidated, ergonomically optimised, weight optimised, heat or fluid[11] flow optimised, etc. Combined with the low capital investment needed[12] for

[11] Fluid means gases and liquids.

[12] Using AM for a project is considered a low capital investment as the needs for tools and tooling is lessened, and not needing as much human resources in developing tooling and preparing computer aided manufacturing thereof. Although the AM machines are still expensive, meaning that in one way

printing, parts could more easily be customised than conventional manufacturing. [87]. The saying that only the imagination sets the limits is truer with AM than with other manufacturing methods and it is up to the designer to find new ways to satisfy the customers through the possibilities gained with AM.

These redesigns and innovations that AM enables for the end product could add value to the customer by affecting the customer in various ways [98, p. 54]. The price tag, the added functionality, fulfilling of expectations, status of owning the product, etc. all contribute to the perceived value. If it costs more it needs to be motivated, it has to be a balance between the costs and the customer value. As customer value is subjective, the value gained from inventions and redesigns are in some instances difficult to define and predict and should be evaluated for the specific project.

As previously stated, the complexity is possible even with RT. Though perhaps less so than with RM as the design has to take consideration to the process in which the end product is created. For example; if it will be casted it has to have a geometry which can be filled out properly; and the tooling needs to be removed in one way or another. Design freedom in the end product with RT entails tooling that are destroyed somehow, burned out, heated away, dissolved using solvent, removed with force, etc. Making disposable tooling directly with RT means that at least some of the tooling cost is per unit and not as an overhead as usual.

AM could even turn out to be more cost effective by skipping at least some of the tools, tooling and assembling otherwise needed, which is even more prominent if several components are consolidated into one [32, p. 288] – which is easier for a more complex end product.

4.3.2.1 Part Consolidation

By the increased complexity provided by AM, several components could be merged into a more complex component and perhaps even improve performance at the same time. This naturally means that the need of tools and tooling are lessened. It also means that the number of assembly operations, need of assembly tooling and logistics are reduced which possibly leads to even greater cost savings [32, pp. 288-289]; [98, p. 54].

It is also possible to integrate mechanisms in one print such as revolute joints and translational joints in some machines. And it is also possible to imbed inserts during the print, such as nuts or even kinematic joints. [32, pp. 292-294]. However, how useful integrated mechanisms and imbedded inserts with AM are for automotive needs should be further researched for the specific use.

---

or another the capacity of the machine needs to be used enough for it to be economical – whether this entails an in-house investment or using a service bureau.

4.3.3 Manufacturing Aids

At a production site, once every bits and pieces have been fabricated they need to be transported, painted, assembled, inspected, etc. Each component is handled somehow which leads to the need for manufacturing aids such as jigs, fixtures, guides and covers. [99].

Although these do not necessarily change the end product notably they could be playing a great role in quality assurance and production efficiency [99]. By providing better designed manufacturing aids to the workers, it might perhaps reduce the physical and psychological strains of the work, and lessen the risk of diverse mistakes such as scratches on the product.

There is also the question of quantity, how many manufacturing aids are needed. And whether or not the design advantage should be used in the production aid, read the previous sections on this (end products with conventional design and end products with AM design advantage).

4.4 AM in Services

AM could enable services towards customer, such as offering printed alternatives to obsolete parts in the aftermarket and offering services in customising the car were the customer could be involved to a greater extent. When used wisely, a service towards the customer could bring new business that customers are willing to pay for.

Another type of AM services are the ones used internally in a company to enable using AM in development and production or bought services from service bureaus. If machines are available in-house, the company can provide its internal customers with services in printing and knowledge thereof, otherwise the company has to rely on service bureau alternatives. Having a own machine naturally means a greater flexibility in the communication, better know how within the organisation, quicker turn around than outsourcing, etc. – the risk is though that you get stuck with a machine that might be outdated any day with quicker and cheaper machines on the horizon. And there is a risk that a suitable machine or material is not available for the needs in the specific project, e.g. in Sweden today it is much easier to find service bureaus within plastic AM than metal AM.

4.5 Some Specific Areas

It is for some areas difficult to separate between tools, tooling, end products with conventional design, end products with AM enhanced design and services – as it might belong to one or more of these. Therefore some of these uses are presented here.

The readers should note that there are more uses of AM than presented in this chapter and should try to come up with other areas themselves that would suit their specific needs – thinking outside the box.

4.5.1 Minimising Environmental Impact

Inventions and improvements in design could be making a car more environmental, but the process in itself can also be more environmental friendly. Compared to the original solutions, using AM could perhaps better utilise materials, minimise the development and manufacturing carbon footprint, improve the carbon footprint when the car is in use, etc.

From a material utilisation aspect, AM could be very effective. The design could be optimised for lightweight and thereby decreasing the fuel consumption over the life cycle of the car. The material utilisation is better with AM compared to milling were much of the base material are milled away when creating the part. And even casting requires more material than necessary due to constraints in the process of when the part is formed, e.g. the walls might need to be thicker and the overall design constraints might lead to a design that is not ideal [100, p. 3]. Therefore, even in the development of products the overall usage of materials might be possible to reduce.

Other environmental aspects could be; energy consumption, moulding and casting in general requires much more energy than modern AM machines; carbon footprint in logistics could be reduced by making production local; overstocking; etc. [100, p.3]; [17, p. 179].

For a complete analysis though, the sustainability over the entire life cycle needs to be evaluated. From the raw material to the disposal of the consumed product. However, the research on the sustainability of AM so far seems to be limited and quite few has attempted full life cycle analysis.

4.5.2 Designed Around You

Volvo Cars' design strategy "designed around you" describes a philosophy which is both human-centric and luxurious [2]. With the opportunities AM provide, new products and services towards customer are enabled if the requirements are fulfilled.

If the design advantage of AM is fully used, new human-centric innovations and radical redesigns are made possible.

Parts could perhaps to a greater extent be customised, meaning that the number of pre-set options to the customer could be increased and involving the customer in the design are made easier. [87]; [98, p. 54]. Customisation is not only personalisation though – with a design that is better suited to the customer, ergonomics could be improved.

4.5.3 Opportunities in Logistics

With AM the need for logistics may be reduced, e.g. if the production site could be localised and if parts are consolidated. Other potential benefits are; just-in-time manufacturing and thereby eliminating the risk of overstocking and understocking, and reducing inventory and warehouse cost; localised production and thereby avoiding e.g. taxes and quotas, and reducing lead-time; and avoiding the risk of sole sourced components. [17, p. 179]. However all of these aspects are dependent on that there is a suitable machine available at the right place and that the component is suitable to manufacture in AM.

4.6 Future Work

Given the right application there could be a good enough business case to use AM in production for the automotive industry today. As the technology gets even quicker and cheaper it might open up for even more possibilities in the future.

Further studies on this topic could explore RT in greater detail, how AM might add value, mapping out more product and service areas that could benefit by the technology.

As the potentials of AM are widespread over the product development phases, manufacturing and even aftermarket, it is important to provide information to others in how AM could be beneficiary for their specific area or project. The people involved in creating the products and services should try to answer questions on the AM enablers such as the following.

- *How would increased geometric freedom gain your project?*
- *How would just-in-time manufacturing gain your project?*
- *How would increased customisation gain your project?*
- *How would better material utilisation gain your project?*

When new information on the application areas are discovered and how it affect the value, perhaps in literature or benchmarking, this chapter could be updated.

5 Design Methodology

Design methodology is about the defining of best practices to achieve the wanted outcome. It is about knowing the restrictions of a process and the potentials to take full advantage of all the resources within an organisation (such as human, capital and in-house machines). [101, p. 327]. What should the work be like at R&D to take full advantage of AM and which tools are needed in the development?

5.1 Introduction

Among the numerous advantages AM provides, some are easier to integrate in the work at R&D than others. When just printing a conventional design for modelling and prototyping purposes, the needed changes are minimal. However as soon as it needs to be a production ready component and process, it gets more complicated.

First of all, the use of AM needs to be justified. It has to be a component where the value outweighs the barriers, but there also might have to be a strategy reasoning behind using AM as discussed in chapter 7. Though the diverse machines available and the possible outcome (in quality of print, costs, lead-time, design limitations, etc.) is not always well defined, which makes it difficult to select manufacturing method or even to consider AM in the first place. Some therefore suggests there should be a design methodology for the inclusion of AM where it is most appropriate holistically, instead of just evaluating single and random components [102].

Much of the conventional design theory and methodology still applies to AM while some will change due to the inherent capabilities of AM, this is explained in-depth in [101; 103]. Much of it involves taking advantage of the performance optimisation AM could contribute to in various aspects such as optimising structural safety margins, optimising for light weight and even customisation. While also making sure it meets the product specification, keeping the cost low and considering the environmental aspects. See figure 5.1 for one flowchart on the prototyping phase with AM. A design methodology will also be greatly influenced by the application, such as customer involvement in design or topology optimisation.

As you might understand, this chapter could be quite large. Instead, only the data processing is discussed further.

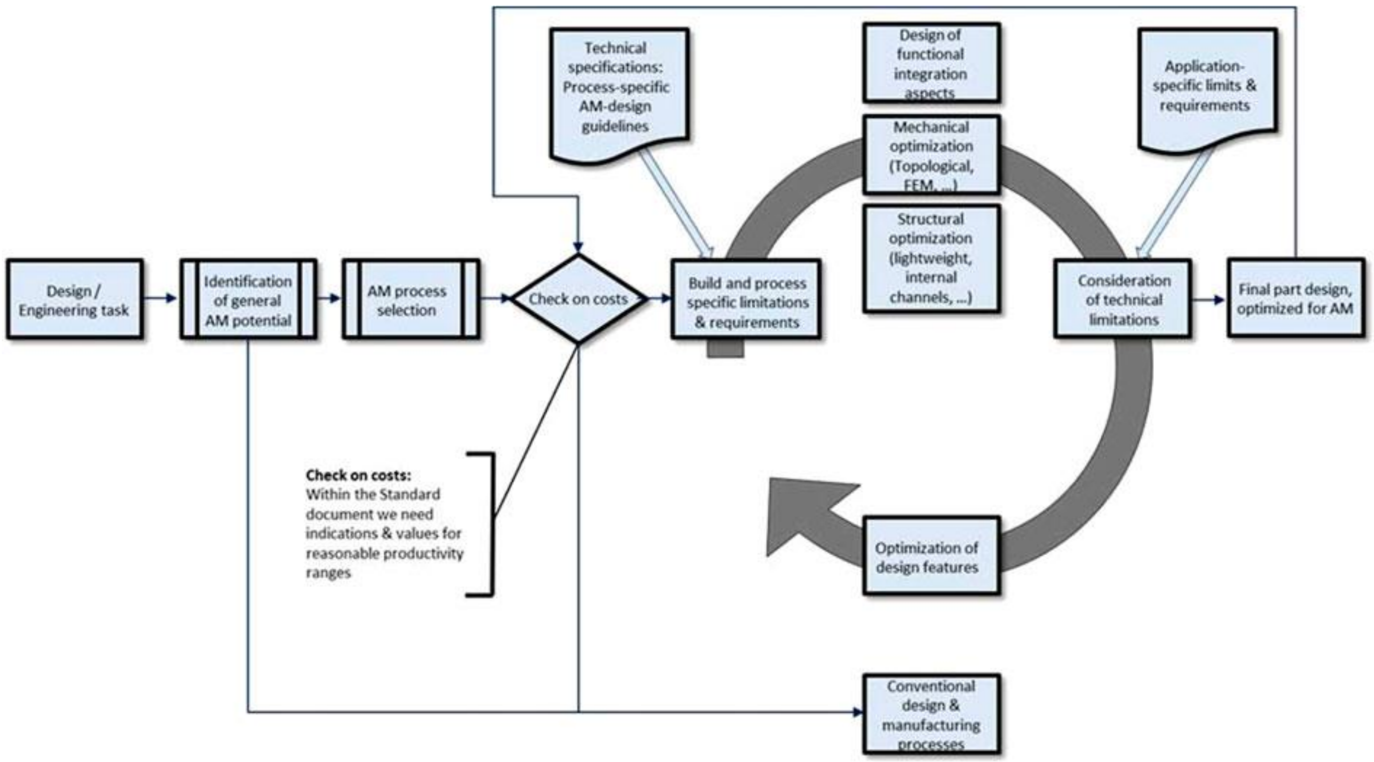


Figure 5.1 A typical process for the inclusion of AM in prototyping [103, p. 231].

5.2 Data Processing

Data processing could be divided into (a) data generation where geometry is modelled digitally in a software or data acquisition where physical information is read by e.g. 3D-scanner, (b) data preparation where the data is transferred into a file format that could be read by the AM machine, and (c) use of data where the data is read by the machine to build the part. [104]. See figure 5.2.

One of the advantages of AM is the often relative ease in which a computer model may be setup in a machine, relatively to the programming intensive machining or having to first develop tools and tooling while also needing to adjust to manufacturing constraints to a greater extent in other manufacturing than with AM.

To start with, the orientation of the part needs to be defined in the machine so that it both fulfils the product specification and take consideration to the constraints in the AM process. The achieved result (quality, economics, scrap, etc.) will be a combination between part geometry and its orientation in machine. Though even if you do exactly as the guidelines suggests for the specific machine, the print still might fail due to unforeseen limitations in the process or even mishaps in the machine – this is especially true with metal AM. If it is due to a limitation in the process, the part might need to be printed in some other way (e.g. divided in several pieces), printed in another machine instead, perhaps even adjusting the design slightly, etc.

Usually, it is not only one part that is built at the same time in a machine. Depending on the printer and the geometry of the part, several components could be built in the machine at once.

Once the orientation for all the parts in the build are settled, it is almost as easy as to press go. Depending on the machine, the file could either be directly printed from the native CAD model (such as formats from CATIA, NX, Creo, SolidWorks, etc.) or be using an interface format (such as STEP, IGES, STL and 3MF[13]). Then the geometric model needs to be converted to a format which the machine could use, a layer representation of the geometry with all the necessary information on the print – this step is referred to as slicing. [104].

Underneath the neat interfaces are the programming of travel routes and diverse machine parameters, which will to some extent impact the possible outcome, the energy consumption and the time for the print. However, this is not always possible to alter yourself. [105].

[13] 3MF is file format released in 2015, it is designed to avoid some of the limitations and issues with other interface file formats [106].

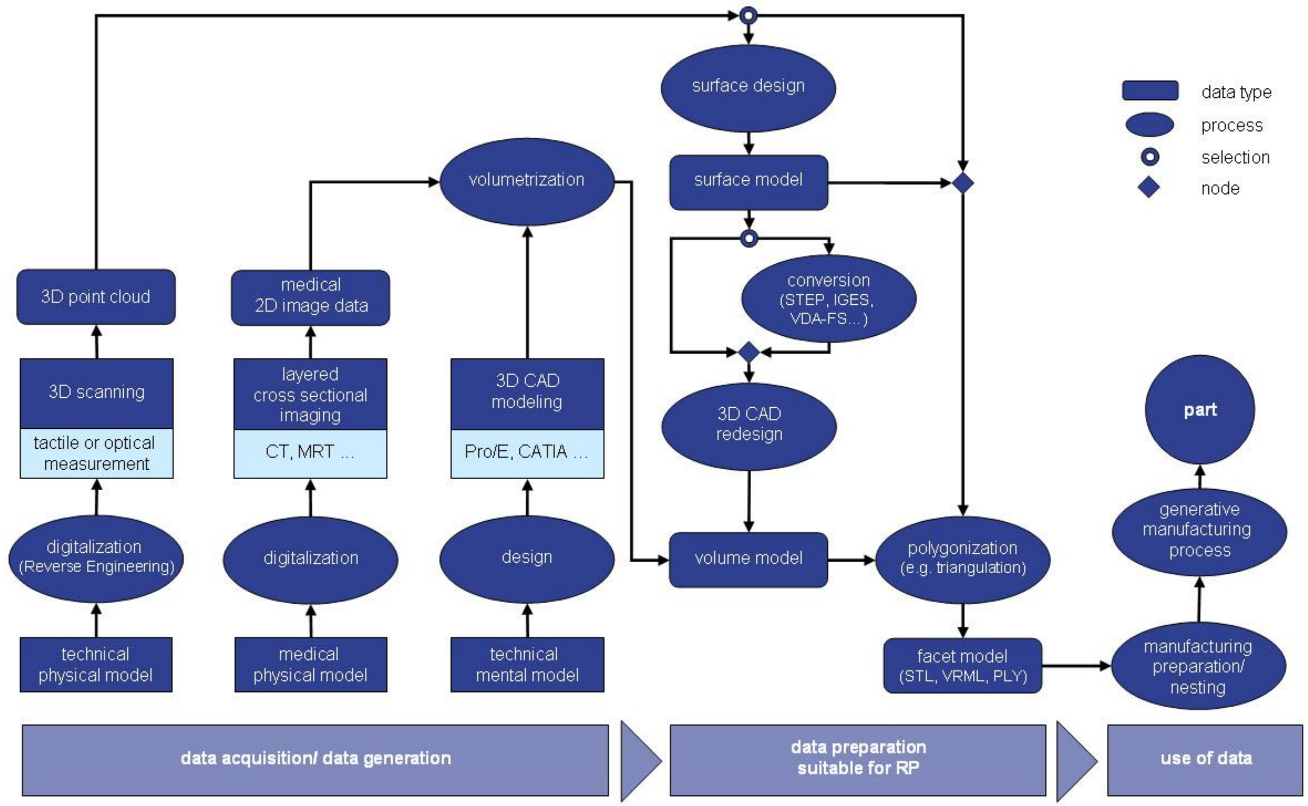


Figure 5.2 Data processing for RP. Image courtesy of Prof. Dr.-Ing. Stéphane Danjou. [104].

5.3 Future Work

This chapter could have been more in-depth on the design methodology of AM. If there would have been time, further literature review could include making detailed maps of when to choose specific machines and how design methodologies should be like for the specific application. And more importantly, adapt the literature to real life. A successful adoption lays in finding tools and ways of working that is tailored to the organisation's culture – or inspire to a new one. Even though the right knowledge exist within a company, the question is whether the ones needing it to take advantage of AM in their project have the proper tools or knowledge thereof.

Creating roadmaps on deciding whether a component is suitable for a certain machine would be valuable. Or even to develop a software that helps in making a wise choice in manufacturing method among all the available capacity and not just AM.

In summary, the future work for design methodologies might be about documenting different approaches and evaluate what works best but also directions on when AM could be used for the specific machines.

6 Case Studies

Two case studies were carried out in this thesis, namely tests on plastic AM components and the development of one metal AM component.

6.1 Tests on Plastic AM Components

Both a test on the post processing and destructive tests were done, and in connection to ordering the components a questionnaire was sent out. The data acquired are summarised in appendix A and, described and analysed in this section. Each material and machine combination were given an identification number which is summarised in table A1.1.

The selection of material was mainly based on the wish to find materials better than polyamide (abbreviated PA, it also goes under the trade name nylon) which also could withstand the heat needed for the quick curing of the coating with primer and painting. The latter is true for all the materials except for ID13 and 14, these however was not in the post processing test.

6.1.1 Ease of Post Processing Test

6.1.1.1 Execution

It has been noticed by painters at VCG that the ease of post processing with AM is dependent on material, component complexity and its orientation in the machine when it was built. In the hope of finding a better material for this, six different machine and material combinations was chosen. As a benchmark object the painters chose a component with a mixture of complex features and some less difficult surfaces.

Four out of the six printed components were made out of PA which could be conditioned in lukewarm water to increase ductility. This happens naturally over time as it age and attracts the humidity in the air. [107]. By conditioning the part though, the increased properties could be used directly for e.g. snap-fits [29]. If this water dipping affects the ease of post processing is unclear, however as it allows for more uses of the print it was decided to dip them in lukewarm water and then let them dry out properly.

The testing involved manually washing, filing, grinding and coating with primer, and was carried out by a professional painter at VCG. For a good comparison, only one of the symmetrical halves were processed.

It would have been interesting to also test a smoothing station from Stratasys which reduces the stepping effect for at least some of their ABS and ASA materials. [108]. This was not done however.

6.1.1.2 Analysis of Results

The easiest material to post process was ID12, a completely new material for VCG.

ID1 and 13 were considered impractical as the defects of the prints made it difficult to process. It was noticed after the test that ID13 also broke easily, perhaps it was not an ideal material to cure in an oven or maybe the quality of the material or print was at fault. In the destructive testing ID13 proved to be more fragile than the others, see table A1.13.

The ease of post processing for ID5 and 6 were comparable to each other, they were printed in different machines (and belonging to the same process category), were oriented differently in machine and had the same material[14]. ID9 which used a machine within in the same process category as ID5 and 6 was also comparable to these two. The stepping effect was more notable on ID6 and ID9 which according to a technician was at least partly a result from the different orientation in machine. ID1 which had a similar material to these was printed in an entirely different type of machine, however compared to the others it was considered impractical as it required a lot of work even without the defects.

The paint did not stick to ID13, perhaps cleaning it with an alcohol based cleaning liquid before would have helped to remove any residue from the support material.

6.1.1.3 Lessons Learned

For mass production, it might be out of the question to paint a plastic AM component especially as the alternative might not require any painting at all. However it might be beneficiary in modelling, prototyping and smaller series. See table 6.1 for the lessons learned.

[14] It was not the exact same material as this machine uses powder in which unused powder from previous run is mixed with the new powder. The ratio between the new and reused material might differ. There is no data on this ratio neither was there any notable difference in the post processing.

Table 6.1 Lessons learned for the ease of post processing test of plastic AM components.

	Lessons learned
7 AM categories	There is a correlation between ease of processing, material, orientation in machine and type of machine.
Application areas	N/A
Design methodology	Designing for ease of post processing should be considered, both in the geometry of the component and in selection of material. It seems that for the ease of post processing the choice of machine is not as relevant as the choice of material. It is important to properly communicate what is desired in the print so that the best result in surfaces can be achieved through orientation in machine and the choice of the material.
Implementation of AM	N/A

6.1.2 Destructive Tests

6.1.2.1 Execution

It is important to have a good understanding on how different print parameters alters material properties as these are used when designing components, especially in AM as the outcome of the machine often is anisotropic (material properties dependent on orientation). But also to know in which way these tests have been carried out, if they have not been tested in the same way the result will not be comparable. Even though the standard is often stated, the full procedure are not always – some variables that is optional in the standards could differ, for example speed. The layer thickness used during the testing of material properties in not always stated either.

Two destructive tests have therefore been conducted according to the standards ASTM D638 for testing of the tensile strength and ASTM D256[15] for testing of the impact strength. Both of these standards are specific to polymers and describes exactly how the test should be carried out and the geometry for the test specimens, see figure 6.1. As the material properties might be orientation dependant, the test should ideally be built in at least three directions – for this case it was natural to choose specimen on its edge, flat and upright. See figure 6.2. For a statistically reliable result a larger quantity should be tested, for this test though it was decided to print at least three per machine/material combination and orientation in machine.

Even the placing in an AM machine could matter, this was not tested for and no data were gathered on this. When choosing layer thickness, it was opted for a common

[15] The ASTM D256 was chosen over ASTM D6110 (Charpy impact strength) as D256 was more common in the material data sheets in the AM materials used in this test. Results from these two tests cannot be compared even though they share the same units.

layer thickness of 0.12mm to reduce the number of variables which could affect result. This was not always possible though, due to constraints in the machines or even the combination machine/material. ID1-4 and ID13-15 differed from this value.

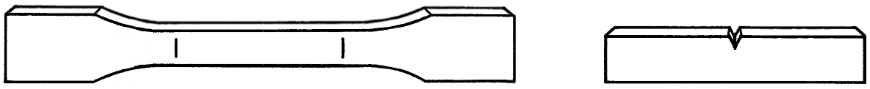


Figure 6.1 Test specimens of the tensile strength test (ASTM D638) with its two gauge marks and the Izod impact strength (ASTM D256). See figure A1.1 and A1.2 for exact measurements.

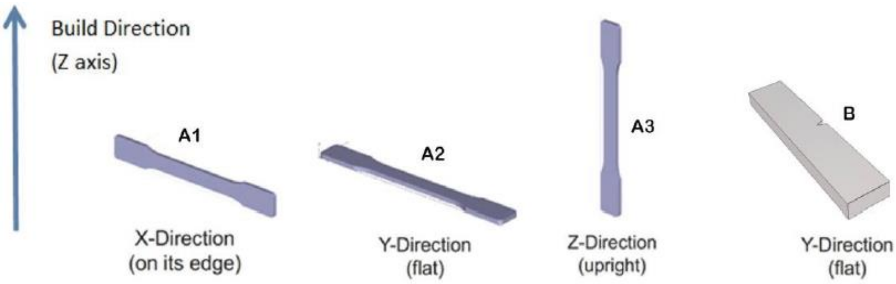


Figure 6.2 The chosen orientations of test specimens when built in the machine.

6.1.2.1.1 Pre-Processing

The way samples are prepared before the testing is important to achieve accurate results. All test samples were conditioned right before testing with a 50 ± 5% room humidity and a temperature of 23 ± 2°C for 96 hours.

Some of the specimens were aged[16] beforehand. Eight samples were put in 70 ± 2°C for 800 hours and one sample was put in a humidity chamber with a 55 ± 5% room humidity and 70 ± 2°C for 500 hours. The original plan was to age all these for 1,000 hours, but was not possible due to time constraints and a problem with the humidity chamber. Time, temperature and humidity can be chosen for the specific project. For comparable data, test specimens need to be treated the same though.

6.1.2.2 Testing of Tensile Strength, ASTM D638

A total of 120 test specimens were printed and tested. For test data, see table A1.3 to A1.11 in appendix A. When two of the machine suppliers already had printed the specimens it was discovered that the specimens had two indents on one side (5.187mm long, 0.125mm wide and 0.5mm deep) representing the gauge marks as

[16] Polymers exposed to heat under a longer time shows the same material properties as though they have been aged for real under an even longer period of time [123].

seen in figure 6.1. As it was too late to do any changes it was decided to continue printing with indents. To get some indication on how the indents might affect the result separate samples was printed without the indents.

- *Conditioned & without indents:* 7 samples were done. Most often QTY3 for each of the orientations in machine (on its edge, flat and upright). In total 20 specimens were tested.
- *Conditioned & with indents:* 26 samples were done. Most often QTY3 for each of the orientations in machine (on its edge, flat and upright). In total 73 specimens were tested.
- *Conditioned & aged & with indents:* 8 samples were done. QTY3 for each of the orientations in machine (on its edge, flat and upright). In total 24 specimens were tested.
- *Conditioned & aged with humidity & with indents:* 1 sample was done. QTY3, oriented on its edge in the machine. In total 3 specimens were tested.

The tensile testing machine works by clamping the test piece vertically between two jaws. An extensometer is then mounted on the test piece, measuring how the test specimen deforms under the load it is put under during the test, see figure A1.4. The machine is then started and pulls the test specimen with a specified speed. A speed of 5mm/s was chosen as it gives a good compromise of the time it takes to test and accuracy – 5mm/s was chosen as it is the same as stated in one of the suppliers' material data sheets and would therefore give more comparable data, in the standard it is possible to choose either 1, 5, 50, 100 or 500mm/s. The machine continuously elongate the specimen with this speed until it breaks. The machine measures with a 20Hz resolution, the force needed to move with the set speed and the elongation of the test specimen.

From this data the tensile strength and the strain can be calculated – both the ultimate (at break) and at the point of yield (where the material begins to deform irreversibly, the deformation before that point is more or less linear). And with the data at the yield point, the tensile modulus can be calculated. These calculations are further described in appendix A.

To find the yield point to start with, a graph was plotted for each of the specimens (with the load on the y-axis and the extension on the x-axis) and a trend-line was fitted to the graph. As the graphs for these materials do not have a distinct point for the yield (as is usual for polymers), a coefficient of determination was used to determine where the linear properties end for each test specimen.

6.1.2.3 Analysis and Discussion on the Tensile Strength Test, ASTM D638

The data of this test is naturally limited to the specific testing procedure in this study and to the specific machine/material combinations. And due to the limited quantity of test specimens in the samples, the values are not statistically reliable though it may provide some clues.

During the testing of ID1 orientated on its edge, which were the first samples to be tested, it was noticed that the extensometer was gliding on the samples, and it was still gliding on the samples even if the clamping force was increased. This would explain the low elongation at break, as the machine continues to pull the sample but not registering any increase in elongation. With the same clamping force used on all samples, it might have compromised the data on the samples without indents, as the extensometer acts as a separation point. To get away from this problem an optical extensometer should be used, which leaves the samples physically unaffected. With the non-aged samples and the aged samples not being tested at the same time, different set-ups were used in the machine, which might have affected the data. As no testing on this have been conducted, no real conclusion can be made on the effect on the test results.

It was problematic to determine the specific point of yield in the measurement data went from the elastic region to plastic deformation. The same coefficient of determination was used for all the test specimens, this made the work easier though might compromise the data somewhat. This might explain the relatively low yield elongation and therefore also the high tensile modulus when compared to the stated values of the manufacturers. Another aspect that could have resulted in better data is choosing a lower speed for the test, however this would have increased the time needed for testing and the processing of data afterwards. A lower test speed might also change the stress-strain curve, but this needs to be evaluated with more testing.

The specified data in the material specification sheets are not directly comparable to the values in this test as the procedure might differ and the indents most of the test specimens makes it even more difficult for a direct comparison – on a closer analysis, the stated values and the values from this test often showed a clear correlation, both with indents and without. It might even be possible to do a correction on some of these values so that the values could be compared directly. The most data points (and therefore the most reliable) that could be used for a correction between the suppliers were with indents. This means that test specimens with the same indents (and tested using the same procedure in this study) could be transformed into data that is comparable other suppliers and thereby both see the effect of the indents and get comparable data. One important finding in this study is that the correction needed was unique to each supplier in this test. As the speed was chosen as the same as one of the suppliers used in their test, eventual errors in testing and other eventual differences in the procedure could be corrected for in all the data (given that there are enough samples to compare) – there was however not enough samples without indents (and sorted per supplier) to make such a correction. As a reliable analysis of errors in this test cannot be made, the data should not be entirely trusted – it could still serve as an indication though.

The mistake of including indents provided some insights into how stress raisers might affect the result depending on machine/material combination and orientation of test specimen when built in machine. See the graphs in figure 6.3 to 6.7.

In the test data, the yield data does not change between the sets of test specimens. When it comes to the ultimate tensile strength (UTS) and maximum strain, there is a substantial difference, especially for the specimens printed on its edge (16% difference) or flat (10% difference). For the elongation there is an improvement of over 300%, see figure 6.7. This shows how important it is to avoid stress raisers in the design of components if it has to endure high loads, perhaps taking special consideration to this under the development phase.

Taking consideration to the build orientation, it is hard to make any real conclusion on parts built upright, as there is only one ID tested with this build orientation, which makes it hard to make any general conclusions, but for ID5 there is not much of a difference with or without indents. At yield it performs a little bit lower but at break both the elongation and UTS is better than with indents.

For the other build directions it is hard to find a general trend, as the properties seems to be material dependant. But looking at UTS, it seems that the parts printed on its edge show a bigger improvement than if the parts where printed flat. For elongation at break, to opposite appears to apply.

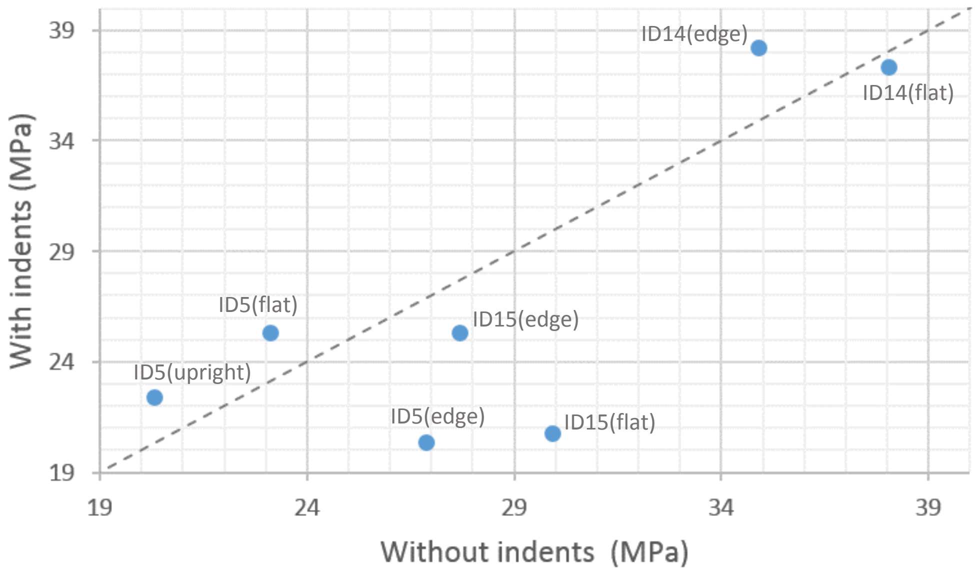


Figure 6.3 Tensile strength at the point of yield. If the data point is above the dashed line then the value for the samples with indents is lower, when it is below it is higher.

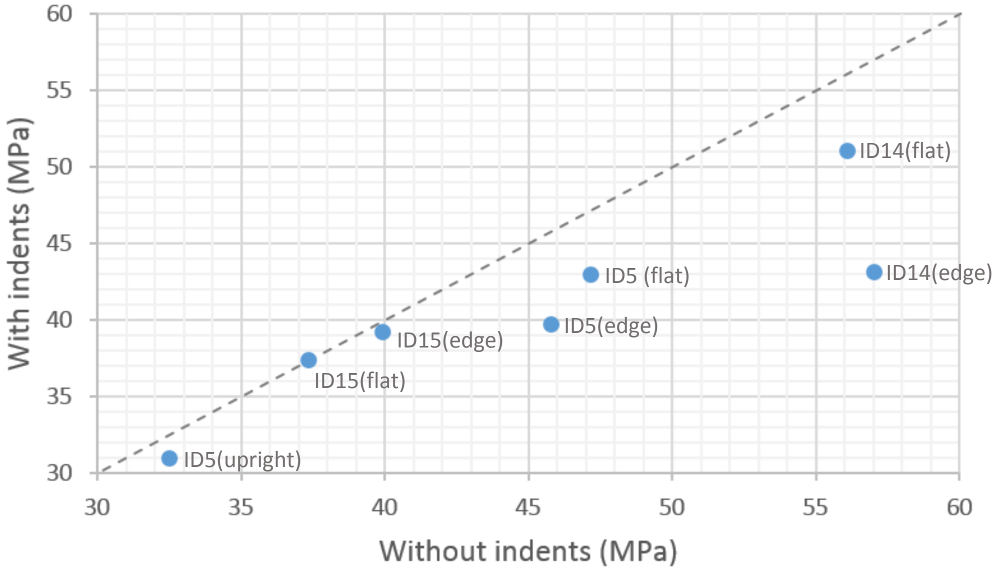


Figure 6.4 Ultimate tensile strength. If the data point is above the dashed line then the value for the samples with indents is lower, when it is below it is higher.

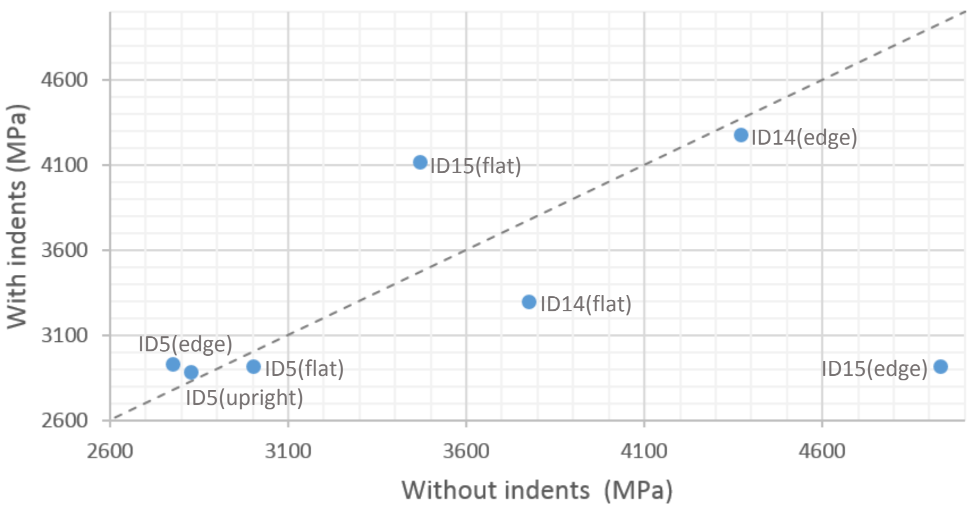


Figure 6.5 Tensile modulus. If the data point is above the dashed line then the value for the samples with indents is lower, when it is below it is higher.

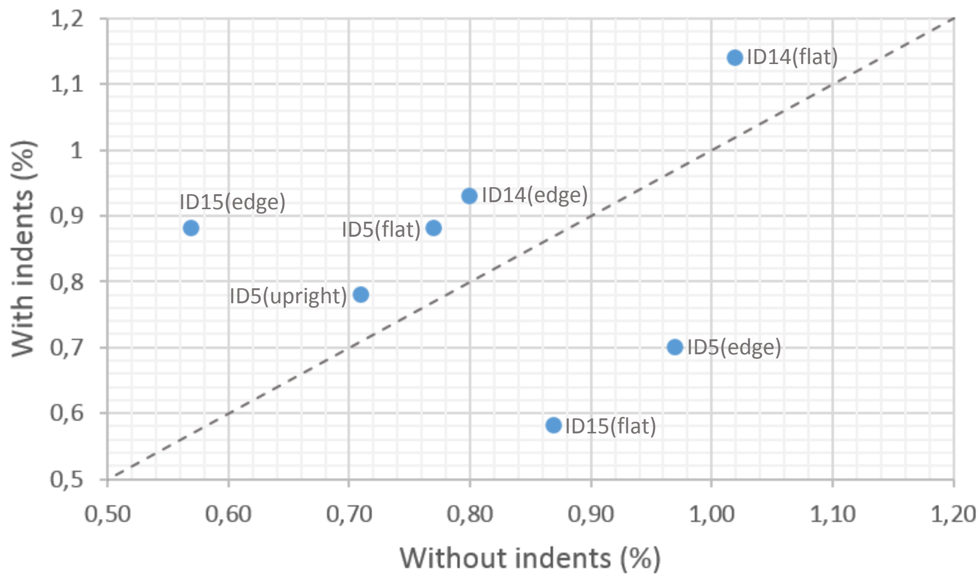


Figure 6.6 Elongation at yield. If the data point is above the dashed line then the value for the samples with indents is lower, when it is below it is higher.

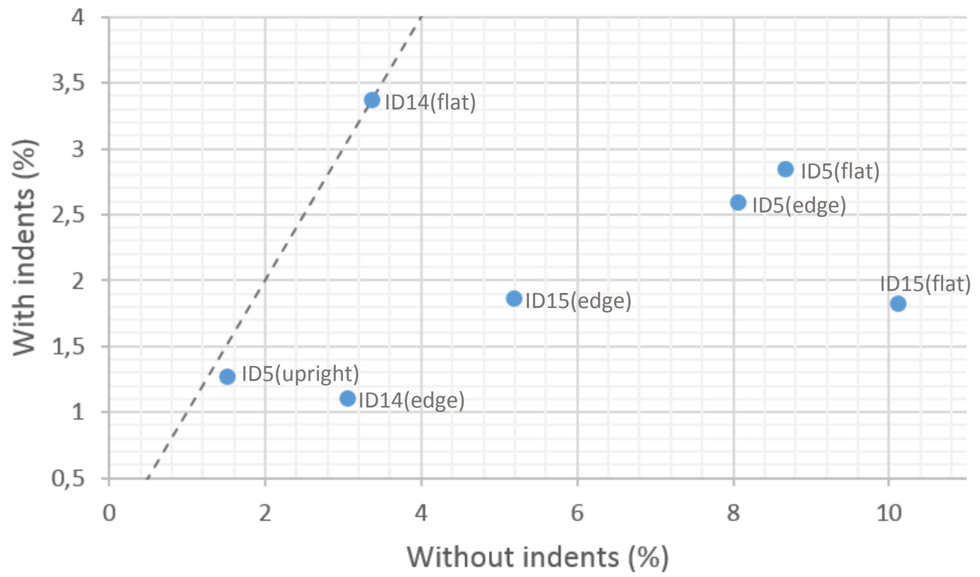


Figure 6.7 Elongation at break. If the data point is above the dashed line then the value for the samples with indents is lower, when it is below it is higher.

The material properties also changed with ageing. For ID1, all properties were improved with ageing, most notably the improvement in UTS for the samples that were aged for 800 hours. For ID6, 9 and 12, there is a trend of the tensile strength at yield going up, but the elongation at break is lower than for the non-aged samples. ID12 also shows a 20% increase in UTS. For ID13, no major difference can be seen. See figure 6.8 to 6.12.

For the specimens that were put in the humidity chamber, the maximal values obtained, UTS and elongation at break are lower than for the aged only parts. But the properties at yield are improved.

When it comes to build orientation for ID1, parts printed on its edge is showing better results than if printed flat, this holds for all properties. For the other materials, the lack of tested orientations make it hard to draw any general conclusions, and should therefore be investigated further.

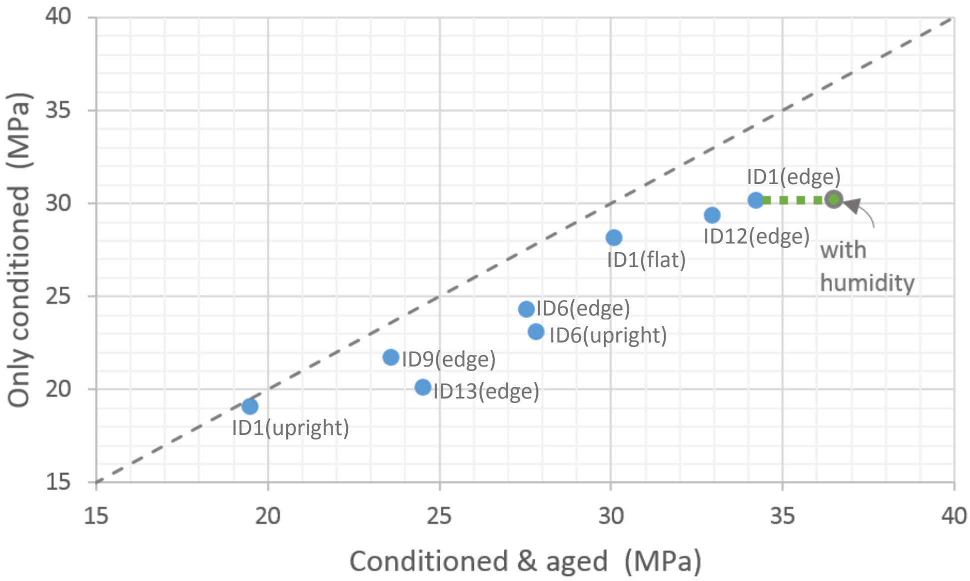


Figure 6.8 Tensile strength at the point of yield. If the data point is above the dashed line then the value for the aged sample is lower, when it is below it is higher.

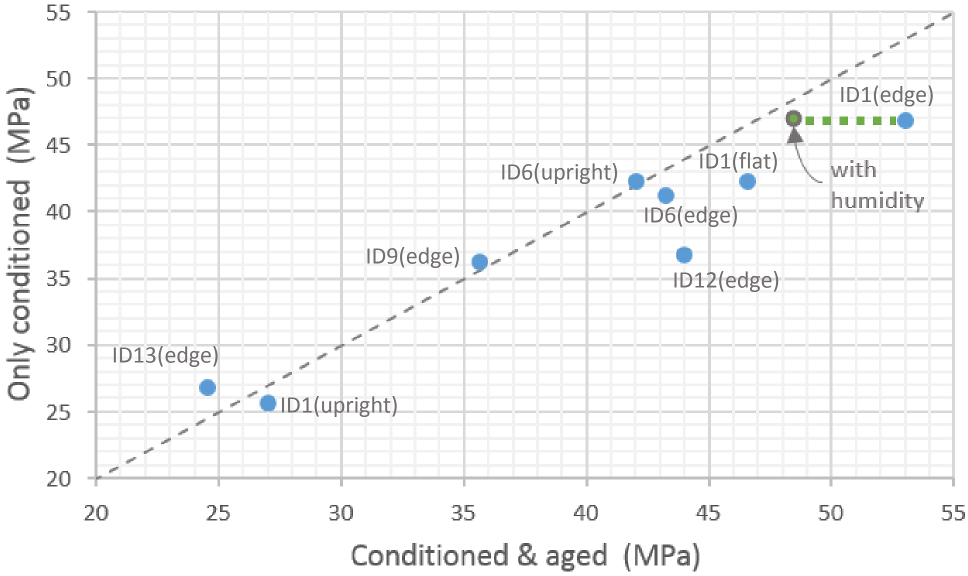


Figure 6.9 Ultimate tensile strength. If the data point is above the dashed line then the value for the aged sample is lower, when it is below it is higher.

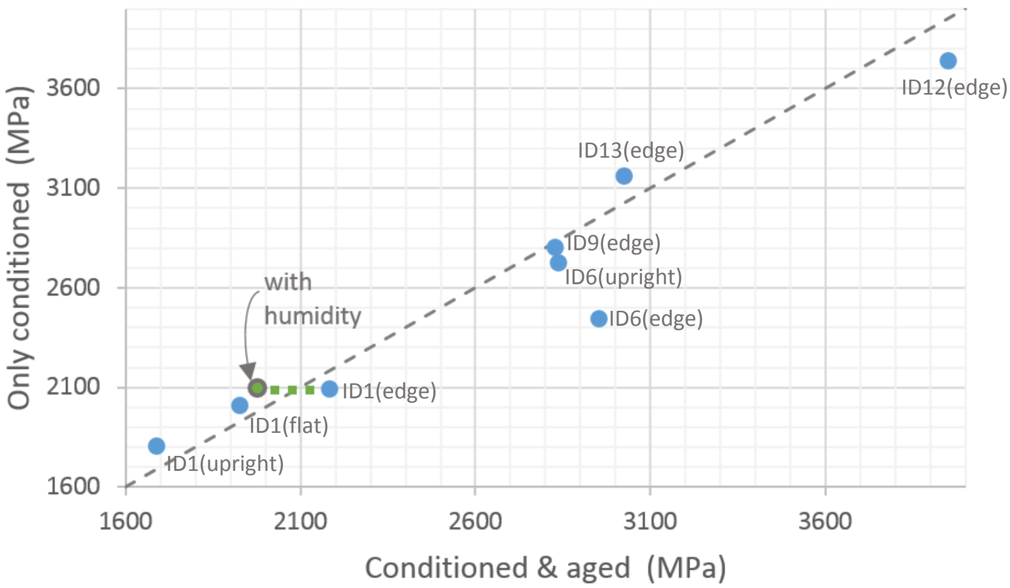


Figure 6.10 Tensile modulus. If the data point is above the dashed line then the value for the aged sample is lower, when it is below it is higher.

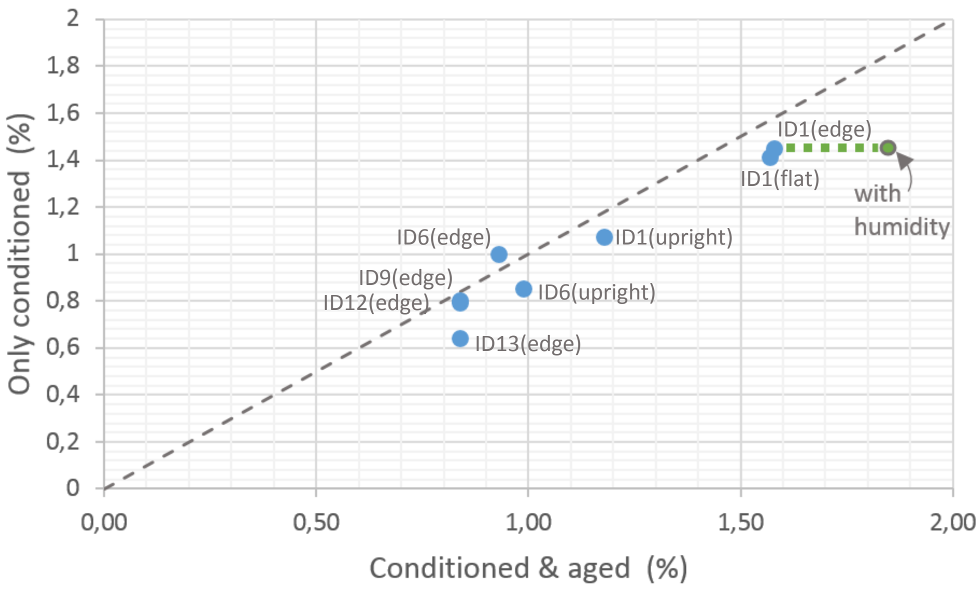


Figure 6.11 Elongation at yield. If the data point is above the dashed line then the value for the aged sample is lower, when it is below it is higher.

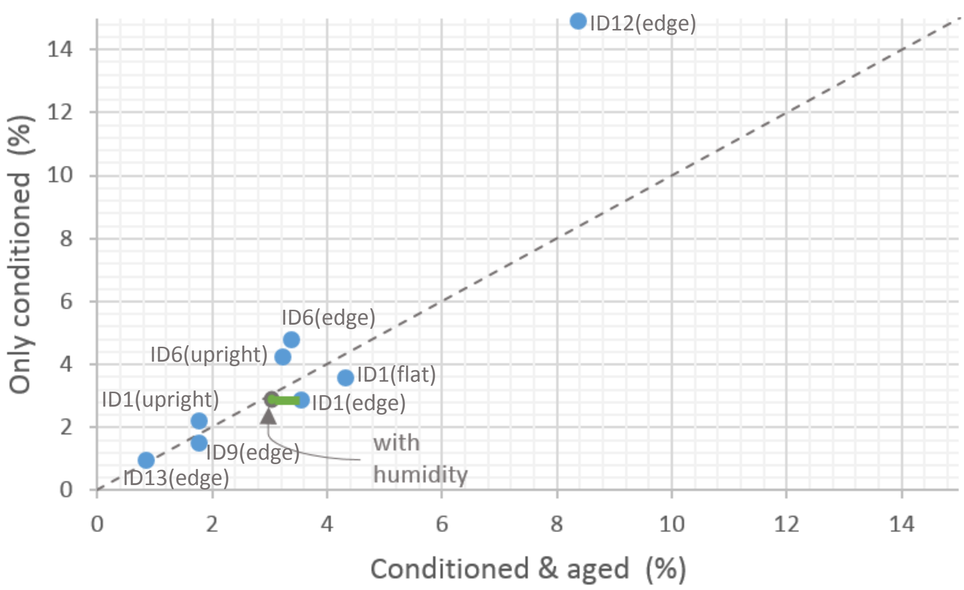


Figure 6.12 Elongation at break. If the data point is above the dashed line then the value for the aged sample is lower, when it is below it is higher.

6.1.2.4 Testing of Izod Impact Strength, ASTM D256

A total of 63 test specimens were printed and tested. For test data, see table A1.12 to A1.14 in appendix A. Due to time constraints only one orientation in machine was tested. The sample was printed flat as this was considered the strongest print direction. For each machine/material combination, most often three specimens were tested. There were two different pre-processing.

- *Conditioned:* 15 samples were done. Most often QTY3 and with the specimen oriented in one way (flat). In total 47 specimens were tested.
- *Conditioned & aged:* 5 samples were done. Most often QTY3 and with the specimen oriented in one way (flat). In total 16 specimens were tested.

The Izod testing machine uses a very simple mechanism for the impact strength test. It uses a pendulum with a set energy level at the bottom of its stroke, and by measuring how far the pendulum moves after hitting the test specimen, the energy absorbed can be obtained. The machine used during the testing had a 4 joule hammer attached, and the absorbed energy was calculated by the machine. See figure A1.5 for the set-up of the machine. The test specimens are mounted vertically, with the notch facing the pendulum and the specimen is mounted in such a way that the middle plane lays coincident with the top surface of the clamping jaw.

6.1.2.5 Analysis and Discussion on the Izod Impact Strength test, ASTM D256

The pendulum used during testing proved to be of a too large energy potential. For these materials a more suitable energy level would have been 1J, but no other pendulum was available. This gives a lower resolution, and for the very brittle materials it is hard to obtain useful data, as the machine gives the same value for all samples. The value should be different as the specimens differs in dimensions. No measuring device were available for measuring the notch, so the dimension from the drawing was used. This will make the data a bit compromised, as the exact dimension is not known and cannot be measured afterwards as the test specimen is destroyed at the notch.

As you can see in the tables in appendix A, the manufacturers does not always provide the material properties for impact tests – at least not without further inquiry. At most five samples could be compared to understand if there was any correlation between our data and theirs. These indicated that the smaller test values obtained in this study were a bit more accurate according to the specific manufacturer's stated values. A comparison like this could either indicate on what they have done differently in their testing and or eventual errors in our study, no such conclusion could be made from these values however.

All of the materials which were based on PA benefited from ageing, the only other material (ID13) in this test was affected slightly negatively. See figure 6.13. As previously stated in the ease of post processing, PA attracts water over time which results in changed material characteristics. Perhaps the aged PA samples attracted more water than the other samples, no data on this were collected. In future tests it would be interesting to see how dipping these in lukewarm water would change the data in a similar way as with the humidity sample in graph as in figure 6.13.

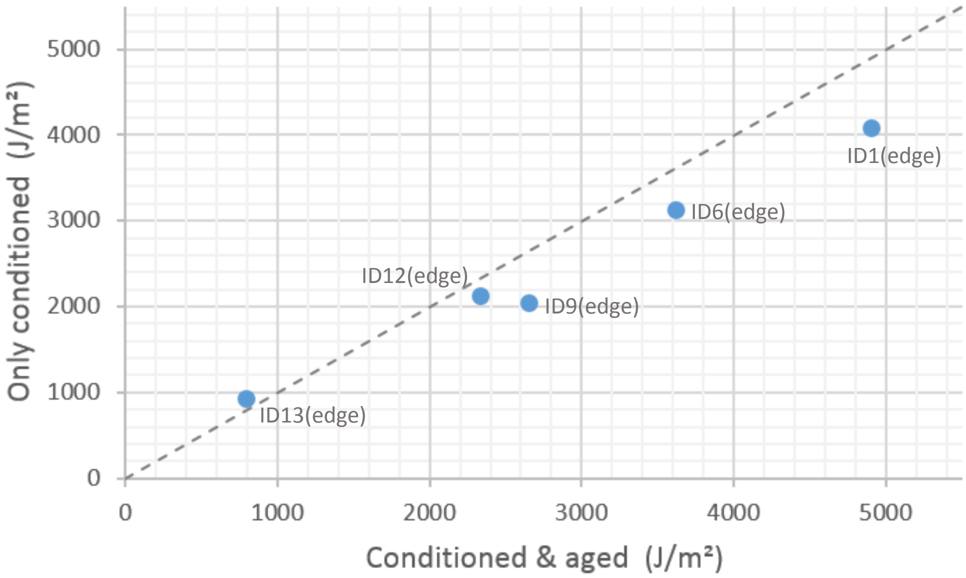


Figure 6.13 Comparing impact strength on aged test specimens and their corresponding non-aged sample. If the data point is above the dashed line then the value for the aged sample is lower, when it is below it is higher.

6.1.2.6 Lessons Learned

The lessons learned during this study is summarised in table 6.4. Some other aspects that would have been interesting to test is how various parameters during the build would affect the result.

- How would placing in machine affect the result?
- How would various layer thickness affect the result? How would this affect the ease of post processing and the material properties respectively?
- How would materials behave under fatigue?
- Would testing of other print orientations be relevant?
- How would dipping printed PA in water affect material properties?

See table 6.2 for the lessons learned.

Table 6.2 Lessons learned in the destructive testing on plastic AM components.

	Lessons learned
7 AM categories	Some conclusions could be made specific to the variables in this study. The variables include material, machine, orientation when built in machine, pre-processing, layer thickness etc.
Application areas	N/A
Design methodology	Choosing the right material and orientation of the part is important to obtain the best properties of the part and both might need to be considered during development. Stress raisers should be avoided if possible or carefully planned out with the choosing of the orientation of component in machine. Even small ones (as the indents in this study) could have a large impact on the function of the component. Having a material database would be valuable, though it might be misguiding if the procedure of the testing differs as these are not directly comparable. Therefore it would be good to either have an independent tester or even more strict guidelines on testing procedures at least for general use.
Implementation of AM	N/A

6.1.3 Questionnaire

The questionnaire primarily searched for aspects that might affect business cases, both when investing in a machine and to evaluate if pricing of AM services are reasonable. Much of the information gained in the questionnaire are only relevant to specific machines and some info are common knowledge to the specific process category of the machine. The questions involved surface quality, maintenance of the machines, time aspects of running the machine, materials and tolerances. The full questionnaire and the details will not be presented in this thesis.

The choice of material is limited for the machines, and if another material would have been used it might affect warranty. Even if a material is possible in a specific machine it might require an additional license meaning more expenses. Base materials should be handled with care, as it might soak up moisture which could affect the result of the print.

Some machines require the print to cool down while others do not. The start-up of machines could differ a lot.

In hindsight it was discovered that it would have been interesting to see how long time it would take to change a material as this could be considerable. It would also be of interest to ask if there are any components of the machine that needs to be replaced over time and how often they need to be replaced, such as the printer head, building plate, etc.

6.1.3.1 Lessons Learned

Doing a detailed map of machine specific details in a business case for different types of machines would be valuable. It would help both in wisely investing in a machine and in negotiations with AM service bureaus. See table 6.3 for the learnt lessons.

Table 6.3 Lessons learned in the questionnaire for the test on the plastic AM components.

	Lessons learned
7 AM categories	Some information was learnt specific to some machines and some more in general to specific process categories.
Application areas	N/A
Design methodology	N/A
Implementation of AM	N/A

6.2 Development of a Metal AM Component

If a component is completely redesigned for AM it could bring value that outweighs the barriers, as discussed in chapter 4. It was decided that an existing component should be redesigned for direct part production, partly to gain better understanding of AM in general but also to create a showpiece for inspiration.

Searching for a suitable component is an important task in itself. This is especially true for direct part production as the capacity of AM machines to a greater extent needs to be used for one project.

The chosen component consists out of several sheet metal parts that are welded together. Each of these parts requires tools and tooling during manufacturing, such as stamping tooling, jigs and fixtures. With part consolidation, the costs of tools and tooling may be skipped and the available design space can be better utilised without the need of tools and tooling. For this specific component, it resulted in a weight optimised shape taking the physical requirements into consideration.

Verifying that the component actually fulfils the requirements with the chosen manufacturing method is also an important step, both for proof of concept and to learn more on AM. The plan was to actually print the component and verify both the component and do destructive testing on some test specimens. However the timeframe of the project and the scarcity of service bureaus in metal AM did not allow for it, it was only printed in plastic AM. Some other insights on metal AM were gained regardless.

6.2.1 Part Specification

As the AM component should be able to replace the existing design, no fundamental redesign was possible. The component still needed the same interfaces to other components as previously to function as usual and the design should preferably be within the same design volume so other components are not affected by the change.

With the loading that the component has to withstand, together with the fact that no redesign is possible on the mounting points, leads to that the material used has to meet or exceed the material properties that are used on the existing component. This excludes the use of plastic materials, as for example Windform XT 2.0, a top performing SLS material [109] only has a UTS of 84MPa [110].

6.2.2 Concepts and Concept Selection

To find a more optimal distribution of mass and thereby decrease weight, so called topology optimisation could be made in a computer software with inputs on design space, necessary features of the component, material selection, loads and boundary conditions. Softwares with this functionality makes a simplification of the real life scenario on which it can base calculations on. A larger design space might allow for a better design, still there are some instances where it might need to be restricted as in interfaces to other components.

To begin with, two alternative concepts were therefore evaluated. One using the original design volume and the other one with a 66% larger design space with the risk of affecting surrounding components.

The software used in this project was Altair SolidThinking Inspire, there are other software though with similar or more advanced functionalities. Optistruct or TOSCA for example. To be able to do the topology optimisation, Inspire needs four material properties, namely density, Young's modulus, yield strength and Poisson's ratio. Stainless steel 316L was used during this first concept selection, see table 6.6 for material properties. The component is divided into design spaces and non-design areas for the analysis. This tells the program where it is allowed to make changes to the material layout and where the design should remain unaffected.

The concept with the larger design space resulted in a 5% lighter component than the one based on the original design volume. This was however seen as a too small weight advantage as the larger one will take more time in the printer and therefore likely cost more. And again, using the original design volume means less conflict with surrounding components. Therefore a new design optimised from the original design volume was selected.

6.2.3 Concept Refinement

For this design volume three materials were used for the optimisation to see what sort of weight savings are possible to obtain when designing for AM. The three materials evaluated were aluminium, titanium and stainless steel. See table 6.4. Both the stainless steel and titanium are possible to use for the redesigned AM component, but the yield stress for aluminium is probably too low to be used in this specific case. But as it is a material commonly used in AM it was decided that information on this material should be obtained anyhow.

Table 6.4 Material properties of the evaluated materials [111; 112].

Material	*Young's modulus (GPa)*	*Yield stress (MPa)*	*Density (kg/dm³)*	*Poisson's ratio*
Aluminium, AlSi10Mg	54	216	2.68	0.33
Stainless steel, 316L	138	511	7.99	0.25
Titanium, Ti6Al4V	107	1055	4.43	0.342

The resulting shape when optimising each of these materials for a given design space are different and it is not only the thickness that changes but also the overall shape. Each material is therefore as a concept in itself.

The material cost and the weight reduction can be calculated with the data from the topology optimisation, material specification in table 6.4 and the material pricing from the supplier. See table 6.6. The titanium and aluminium concepts are very close in weight yet these materials have very different material properties, probably as an effect of the loading and the design volume. The steel concept does not show the same weight savings as the other materials, in fact it is nearly the double. As steel is heavier per mass the non-design spaces for this concept will be much higher, this was the main contributor of weight in the heavy steel concept.

Titanium was by far the most expensive, nearly five times the cost of aluminium and more than the double when compared to the steel. Titanium in itself is nearly five times more expensive than both of these and also is more difficult to process in the AM machine as it requires a higher melting point, which further increases the cost compared to the stainless steel. Titanium is therefore no viable option. As previously stated, the aluminium does not meet the requirements on material characteristics – however it might still be a viable option in test objects as it is much cheaper than the concept alternatives. Perhaps the best option for the end product (among these concepts) is therefore the steel version.

The environmental impact of each of these materials, the used machines and the life cycle of the component should naturally also play a role in the choosing of the final concept. This was not closer analysed for this study due to time constraints.

Table 6.5 Results on weight reduction and material cost [4; 113].

Concept	*Material price (SEK/kg)*	*Relative weight*	*Relative material cost*	*Weight reduction*
Aluminium, AlSi10Mg (ref.)	975	1.00	1.00	59.20%
Stainless steel, 316L	1075	1.90	2.09	22.70%
Titanium, Ti6Al4V	4675	1.02	4.88	58.40%

To finalize the component for printing, the rough result[17] from the optimisation had to be smoothed. This was freeform modelled[18] in the program SolidThinking Evolve using the geometry file from the optimisation as a reference. See figure 6.14 for a work under progress. Geometries for both the aluminium and the steel concept were created.

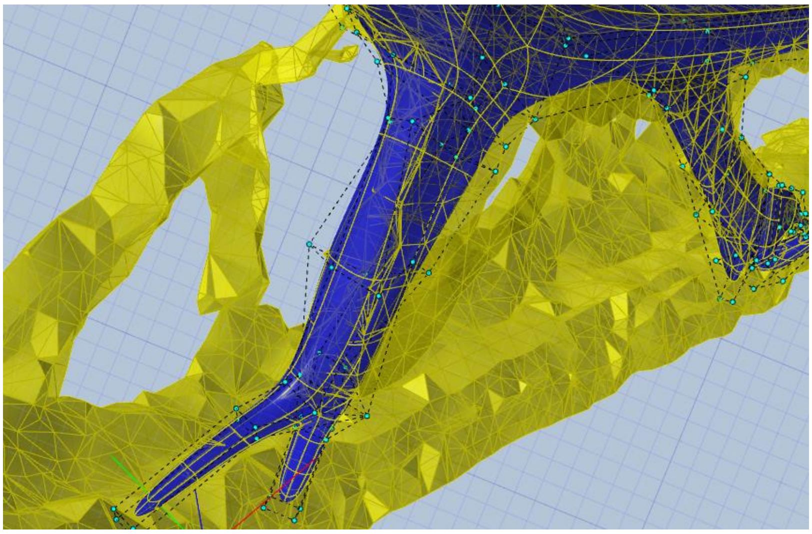


Figure 6.14 Freeform modelling in Evolve. The yellow is the imported result from the topology optimisation, whereas the blue part is the modelled adaption of the yellow. This is not the actual component referred to in the text.

As the reference of the optimised structure is coarse, the result of the modelling will also be approximate. The result should therefore be validated through FEA to make sure it still meets the product requirements. If it does not meet the requirements, more material should be added in the critical areas until these are met. Ideally it

[17] These sharp edges you see in figure 6.14 are the result of how a topology optimization program operates. To be able to calculate these problems, the computer divides the design space in smaller discrete elements – you may call it “pixelated”. The elements which are not needed have been removed.

[18] There are three main types of CAD, parametric, freeform and surface modelling.

should be an iterative process were the created geometry is FEA analysed, topology optimised using the new geometry as a design space and then the changes could be done to the model – and then FEA analysed again. This process could be then repeated until the weight reduction of the optimisation is deemed too insignificant, for the steel version it was iterated until the possible weight savings was under five grams.

The designer does not have to follow the reference from the optimisation fully. The risk is though that many more iterations are necessary to achieve a result that is good enough for the product specification.

6.2.3.1 Quotes from Service Bureaus

When the design of the component was finalised three external service bureaus were contacted for quotes. This quotation was for all three materials to get an apprehension on how the time and cost would differ between the materials.

One of the service bureaus could not print the component as the machine build volume was not big enough. From the second, no quotation was given. The third service bureau could print the component in aluminium, steel and titanium. Two options was given for the steel – either making the component in pieces and then weld it together or print it in one piece directly in a larger machine. Splitting the geometry in two or more parts partly defeats the purpose of skipping tools, it could still be alright for a prototype depending on usage but this was never an option for this study. Printing it in one piece on the other hand would mean much higher costs, one reason is because a bigger machine usually is more costly but it was more linked to the fact that this specific machine is very rarely used for steel – costs of changing material can be very steep for a metal AM and take a long time, no quote was given for this alternative.

Aluminium was by far the cheapest alternative, then double the money and you get the welded stainless steel concept. And titanium is even more costly. See table 6.6. This difference is partly down to how easy the material is to process, the more difficult it is the more expensive equipment might be and the longer time it might take in the machine. As you can see in table 6.5 the material price for steel is twice as much as the cost for the aluminium, as the scale is different to the table 6.5 it cannot be directly compared – however with the real numbers of the material costs and the purchase price it can be concluded that the difference in table 6.5 is more down to the time needed in the machine than the cost of the material (the purchase price is considerably higher than the material cost).

Then there is also the question of quantity, with a higher quantity the price per part will get lower as discovered in this study. The risk of anything going wrong is higher during the first print and the cost might decrease with a larger quantity as a result of streamlining the work. This might be especially true with metal AM as it is more difficult to get right than plastic AM, the first component is therefore usually more expensive.

Table 6.6 Purchase price and time in machine for the concepts [4].

Concept	***Relative purchase price*** *QTY 1*	***Relative time in machine***
Aluminium, AlSi10Mg (ref.)	1.00	1.00
Welded stainless steel, 316L	2.07	2.00
Titanium, Ti6Al4V	2.62	N/A

[a] The purchase price stated below is per each component.

6.2.4 Thoughts on Product Verification and Validation

Verification and validation of products is important in both the development phases and during manufacturing to make sure the component or the system of components meets specification and fulfils the intended purpose. [114].

The component in this study was tested virtually with a so called FEA analysis to make sure it would meet requirements. However these kind of software relies on approximations of real life, if the input for this analysis is not good enough then neither is the result. It is essential that the analyst of the result has an in-depth knowledge on both the process of the AM machine and the build material. Material properties in AM are not always uniform and will depend on many factors in the process but also how the part is oriented and the post processing. The real life scenario of the material properties might be so complex that the available computer aided tools today is not good enough.

There are also several stages of physical verification. When computer aided tools are lacking, early physical testing becomes even more important to decide if AM is a viable option for the specific project. No physical test was made as the component in this study was not printed in metal AM, nor any test specimens. However it was printed in plastic AM. Metal AM is much more expensive, for some early verification and validation purposes plastic AM might be a better alternative.

Verification and validation also exists in manufacturing, in quality assurance of the product and the process in which the component is created in. All requirements should be met regardless of where and when it is produced, in-house or by an external supplier. There is a need to make sure that the process parameters and material specification stays the same as to the original part, something that might be difficult as the technology moves forwards with new materials and machines. If the process parameters does not stay the same, a new certification process might be needed which might be costly.

It is important to keep track of the process and the achieved outcome, to minimise defects and streamline production. Keeping a test record on the products is both for quality assurance to customer and for traceability in the process. It could for example involve printing a test specimen for each new batch, do destructive tests directly on the component or non-destructive measurements on a few or every component. But it could also be to keep track of the process directly, handling of material, inside the AM machine, moving of the printed part, post processing, etc. In this study, at least one of the service bureau offered services on quality check.

Having standardised materials and processes both in machine and around it are in many cases a prerequisite for production. If these aspects are not standardised, the verification and validation processes might be even more crucial and costly. A roadmap of what needs to be standardised in AM and prioritising thereof is given in [115]. The aerospace industry for example is pushing standardisation work forward to meet their strict requirements [113]. To have control over all the parameters that might affect quality, some in the aerospace industry have invested in own machines and done rigours testing. Service bureaus in AM does not always have the preparedness of production prerequisites and often times they do not tell exactly which testing they do – as they are more used to prototypes where it does not matter as much. More transparency would help in bringing AM to production. [4].

6.2.5 Lessons Learned

The lesson learned in this study are summarised in table 6.7.

Table 6.7 Lessons learned from the development of a metal AM component.

	Lessons learned
7 AM categories	Some info on some service bureaus' purchase pricing and time in machine was obtained. Most of this are specific to the component in this study. The info that the price decreases after the first print might be a bit more general.
Application areas	N/A
Design methodology	Service bureaus have knowledge on their specific machines and the associated constraints in design, as a design might change with this knowledge it is important to co-operate. The service bureaus however might not have knowledge or capabilities to fulfil the production prerequisites. Collaboration might have to be both ways.
Implementation of AM	Lack of service bureaus hinders using metal AM or even evaluating AM. Even with a machine in-house there still might be a need to outsource, when there is a lack of in-house capacity and when there is no suitable machine in-house. Production ramp-up and, product verification and validation with AM should also be looked into.

7 Implementation of AM

“The key is for a company to understand where and how to adopt AM to achieve increased business profit” – Phil Reeves [12].

7.1 Introduction

Implementing any new technology presents challenges for an organisation. It might be necessary to do more research on AM, define new roles, educate, reorganising production sites, set up new suppliers, etc. Published research on implementing AM for production are rare though – which perhaps is one reason why “industrial 3D printing” only is at the peak of inflated expectations in the Gartner’s hype cycle, see figure 1.2.

Research conducted by Stephen Mellor at University of Exeter [6] suggests a conceptual framework for implementing AM systems in production. Dimensions that affect the implementation can be sorted into five categories; strategic factors, technological factors, organisational factors, operational factors and supply chain factors. [14, p. 196]. See figure 7.1.

Moreover [6] defines four key phases in the implementation of AM systems; namely developing the business case, the organisational action plan, the operational action plan and the AM supply chain.

The previous chapters in this thesis mainly explored some business case factors including costs and application areas to aid in making business cases. This was attempted by holistically exploring variants on AM processes, what others are using AM for, how AM might add value and how AM might change the work at R&D.

With this chapter, the main focus is to answer when AM could be implemented wisely with the knowledge gained in the other chapters as well as introducing new relevant theory on some strategy and implementation aspects.

> *Present conclusions that aid in defining when AM is suitable for production in the automotive industry today and in the near future in a context that could easily be built upon.* – Goal of this thesis.

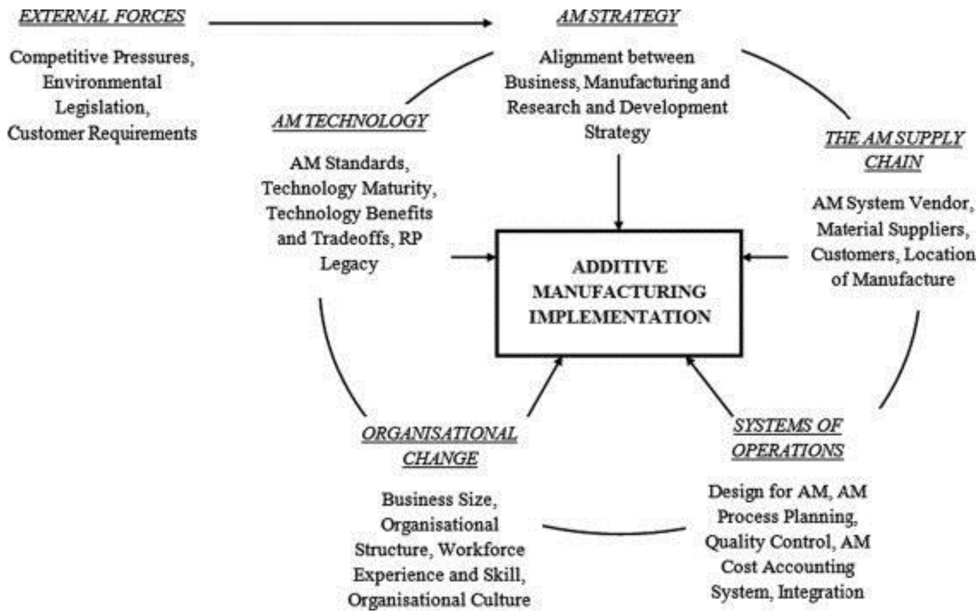


Figure 7.1 A framework for implementation of AM systems in production [6; 14]. Image courtesy of Elsevier [116].

7.1.1 Motivation

As seen in the benchmark; many are on the watch out on how AM could benefit them, some have officially stated that they intend to take it into production and one company[19] is even setting up for mass manufacturing in direct part production. Motivation to implement AM consists of external forces and internal strategies [6].

AM enables numerous opportunities which are discussed in chapter 4. It all comes down to creating, delivering and capturing value, which all three are vital parts of business strategies [81]. To craft an effective strategy in creating or increasing value it has to involve continuously delivering value and capture some of the value in profit in a more or less competitive market. This puts pressure on organisations to be agile in discovering new opportunities. [117]. If AM becomes a mainstream manufacturing method, the improvements that AM enables will perhaps gradually become more expected and perhaps eventually the new standard.

A classic example in missing an opportunity is Facit AB who did not succeed in catching the trend of digitalisation and because of it they lost market shares. They

[19] General Electrics, GE, in the Aerospace sector is currently ramping up for mass production with metal AM. For more information, see page 60 in the benchmark chapter.

nearly went bankrupt in 1972 and was later sold. It is often said “do not do a Facit”. [118]. It is not directly transferable to AM though as the digital breakthrough was product-based technology and not process-based as with AM. It still relevant though. AM could affect many products, manufacturing and R&D and thereby affect the value to the consumer. AM could possibly be a “competitive weapon” in being a game changing manufacturing method just as the digitalisation changed many fields.

> *“Given enough competition, business practices that create the most value will survive, and the competition will ensure that consumers capture most of that value. This is because of personal greed, not in spite of it!”* – Adam Smith’s “invisible hand” [119].

Motivation does not have to be competitive pressure, e.g. it could also be based on the customer’s requirements, legislations and care for the environment.

7.1.2 AM Strategy Factors

The approach for implementing AM will depend on strategic factors, referred to as “AM strategy” in figure 7.1. It is suggested in [6] that before implementation of AM, a strategic alignment must be made between the strategies in business, manufacturing and technology. [6, pp. 79-82].

7.1.2.1 Technology Strategy

A technology strategy is an overall plan of a technology to achieve business targets. Part of a technology strategy could be to keep track of the advancements, invest in machines, employing people to lead the strategy work forward, educate employees on AM, etc. [120, pp. 779-782]. Some issues that may have to be dealt with include the following.

- To be able to choose AM for production in the first place; there need to be available machine capacity, either in-house or outsource alternatives; and there has to be knowledge on the implications of using the specific machine for production.
- To adopt and implement a technology successfully it might be necessary to first overcome cognitive, motivational and informational issues among employees [117, p. 2]. The learning curve of AM is steep though, and keeping up to date with the technology could be fulltime job in its self.
- What makes it even trickier is the large number of machine variants in AM with high diversity in possible outcome, making it difficult to choose a suitable machine. Not investing in a machine though might mean losses in missed opportunities and a low in-house knowledge of AM.

Whether or not the leader or follower approach is applicable for the strategy of a process-based technology is debateable and often criticised for neglecting differences within organisations [6, p. 34]. If the potential gain is high, even the organisations which usually has a modest approach might be persuaded to invest in a technology early on [16, p. 241]. There are a lot of uncertainties with new technologies. It is hard to predict when and if a technology will get more mature and the extent of the possible profit relatively to the existing alternatives. Machine investments can therefore be difficult. [120; 121].

7.1.2.2 Manufacturing Strategy

A good manufacturing strategy could contribute to the long-term competitiveness and performance of an organisation by reflecting on their core values, goals and strategies. Scholars sees manufacturing strategies in different ways, it might be from a process of decision making connected to business aspects or it could be viewed from the various manufacturing-oriented dimensions which contributes to a selling product. There are a lot of literature on this and the interested reader should search for more information himself, and perhaps look up if the organisation has a specific manufacturing strategy or guides to formulate one. See table 7.1 for one example on how a manufacturing strategy could be formulated. [6, p. 44-52].

Table 7.1 Five steps in order to formulate a manufacturing strategy, with associated manufacturing-oriented dimensions that needs to be considered. As proposed in [122].

Corporate Objectives	***Marketing strategy***	***How product win orders?***	***Manufacturing strategy***	
			Process choice	***Infrastructure***
Growth	Product markets and segments	Price	Choice of alternative processes	Function support
Survival	Range	Quality	Trade-offs embodied in the process choice	Manufacturing planning and control systems
Return on investments	Mix	Delivery speed reliability	Capacity size timing location	Quality assurance
Other financial measures	Volumes	Demand increases	Role of inventory	Manufacturing systems engineering
	Standardisation vs. customisation	Product range		Clerical procedures
	Level of innovation	Design leadership		Payment systems
	Leader vs. follower alternatives	Technical support (after sales)		Work structuring
		Meeting launch dates		Worker skill levels
		Existing supplier states		Organisational structure

7.2 Phases of Implementation

According to [6] there are four key phases of implementing AM.

- ***Developing the business case.*** Involves finding the specific areas in which an organisation can benefit from AM and analysing costs.
- ***Developing systems of operations.*** Involves mapping out how AM changes the current processes in design, engineering and production. Issues for the conventional manufacturer would include lack of knowledge on designing for AM, design guidelines, engineering processes and production processes.
- ***Developing an operational action plan.*** Building a supportive structure and culture that aid in taking advantage of AM and to reduce resistance to use AM.
- ***Developing the AM supply chain.*** Deciding whether to invest in a machine or to outsource. Planning for the various steps of the supply chain, e.g. material supply and delivery to customer.

[6] also distinguish three different type cases of organisation who considers implementing AM in production and makes a good case for either of these on which particular order they should go through with the implementation, see his work for more details. The three type cases are the RP convertor, the new start up and the conventional manufacturer. [6, p. 151, 196].

- The RP converter has great insight of AM for prototyping purposes, but they might not have prior knowledge in all the necessities in ramping it up to production. The RP converter struggles with finding a customer base for their new services.
- The new start-up arises from scratch with no established customer base nor any previous process chain.
- The conventional manufacturer has greater knowledge on the production aspects than the other two. However they first might have to overcome some resistance to change among employees.

One interesting aspect that could be made out of his work [6] is that a conventional manufacturer or the new start-up can bridge AM over to production by starting with prototypes and then make the transition to implementation much easier.

These aspects are not just relevant for the organisation planning to acquire an AM machine. If a service bureau just recently made the swap to using AM in production, it is good to know what kind of challenges they face to be better prepared in collaborating with them.

7.3 When to Implement AM in Production

This chapter could go into detail trying to identify parts that wisely could be manufactured with AM – searching through a complete list of every component and system of components in a vehicle, or the tools and tooling that aid in creating the components. Instead an attempt is made to find deciding factors of when AM can be used wisely.

The answer to when AM should be used can only be answered vaguely without knowing the alternative solution, which machines and materials are available, in which way AM adds value, if it suits the organisation's strategies, etc. For many applications though it is necessary to first carry out tests and consult experts.

AM has a rich heritage in modelling and prototyping because of the low barriers in lead-time and cost for the small series, and a low barrier for complex geometry regardless of the production volume. The requirements on prototypes are not necessarily as tough as those on the end product – the lifespan of a vehicle is longer and thereby end products has to be durable, the end product will be produced in a larger scale meaning that the slow AM process might hinder, etc. Tooling on the other hand will have a different set of requirements which will be related to the production volume and the conditions during the forming process. Hard tooling are especially demanding, they could be exposed to elevated temperatures, rapid cooling, forces, etc. which all affects the durability. For all of these areas there are cases in which other manufacturing methods might be more suitable, but it all depends and more research is needed. See table 7.2 for a quick assessment.

Table 7.2 Assessment on when to use AM.

	Should I use AM?
Modelling & prototyping	Yes, in many cases.
Soft tooling[a]	Yes, in some cases.
Hard tooling[a]	Perhaps.
Manufacturing aids	Yes, in some cases.
End products	Perhaps, in special cases.
	All of the above might change in the near future!

The optimal part for AM would probably be described as having a high value and low barriers, and having product requirements that is achievable with an available AM machine. The previous chapters are designed to aid in defining when AM should be used for the specific case, and will not be repeated here. It is not possible to answer the question on when AM should be used in much greater detail on a holistic level other than it has to do with strategy factors and prioritising projects.

7.3.1 AM Strategy Factors

Whether or not a project using AM in production will be feasible are dependent on the organisations strategies.

Some projects require minimal organisational control, though AM with its steep learning curve the risk is that without a dedicated AM group; people might not get aware of the potential of AM in the first place; finding a suitable machine might be too time consuming; finding out what is possible might be too difficult; etc. With a dedicated AM group, coordinated searches can help finding potentials and educate others so they themselves can come up with the idea to use AM. [117, p. 4]. A project is usually constrained by a budget and a time frame, if the knowledge barrier is too high then it might not be possible to even consider or diving deeper into AM in the first place.

When using AM you do not necessarily have to acquire a machine. However if no in-house investments into AM has been made then an organisation has to relay on service bureaus to have a suitable machine and perhaps even provide knowledge. Even if you have a machine you still might have to outsource to some extent.

Products and services towards customers might need to go through portfolio planning. Cost reduction is always welcome but if it even increases cost then it should be motivated somehow, preferably aligning to the organisation's objectives.

7.3.2 Prioritising Projects

It is not always possible to do everything at once as a project does not have unlimited budget nor time and suitable machines might not be available or capacity enough. To make a good prioritising in the first place there has to be projects worth choosing.

For some uses though it is necessary to first find out more information on machines, perhaps doing a case study to see if the project is achievable in the first place. If it is well carried out, a study could provide knowledge to other projects as well. And find even more applications that is possible. A good place to start is often said to be prototypes in replicating conventional designs. This allows for a good base in understanding the AM process, possible outcome, designing for AM, etc.

When a good mixture of possible projects have been established then a good place to start in prioritising projects might be in looking into theory on manufacturing strategy to find the projects that best aligns to the organisation's objectives.

7.4 Future Work

The chapters leading up to this each contributes with information to when AM can be wisely implemented. This naturally means that if any important steps or information have been missed, decisions based only on this thesis might be misguided.

Besides all the future work presented within each of the chapters, it would be valuable to add at least two new chapters. Tools and tooling are very important in most manufacturing settings and could amount to huge amounts of costs, but which tooling exactly is AM technology mature enough for? Verification and validation are essential to any manufacturing settings, how would it change with AM?

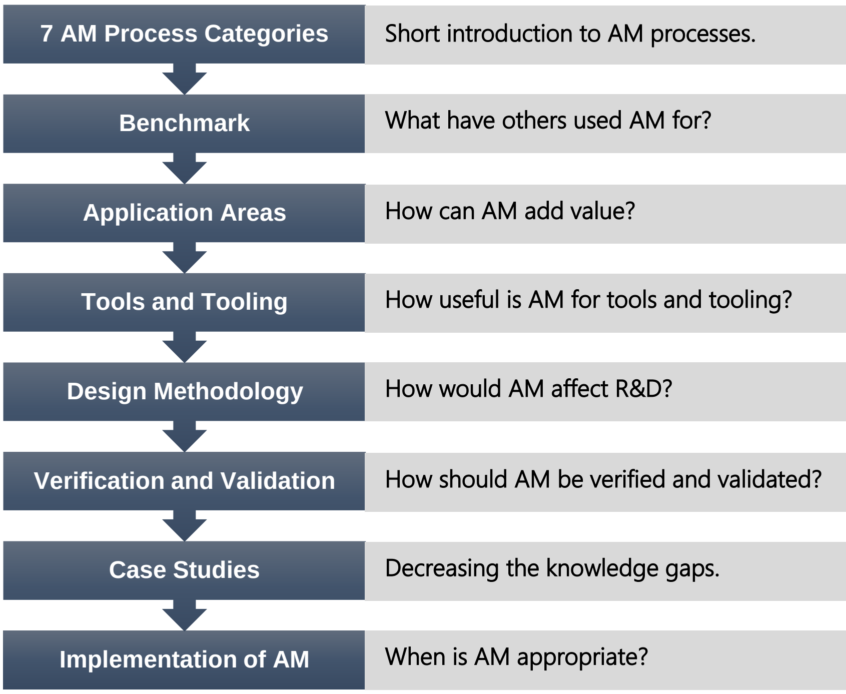


Figure 7.2 Plan of the thesis revisited. The new areas that also should be considered.

For this chapter, it seems that building on the information provided in [6] would be the right step in continuing the work of bringing AM in to production – especially looking closer into the four key phases for implementation he proposes in relation to the strategies of the organisation. These phases could be added as subchapters to this chapter. Also some areas that should be look into are how quality assurance and production planning might change.

AM is under development as it has been for several years now with technical advancements and new research constantly on the horizon – meaning that information often is biased and easily could get dated. Many predicts AM will get quicker and less expensive within just a couple of years, and perhaps even with a better outcome in quality. These advances would in turn make more usages possible and make implementation of AM even more realistic.

It seems that it would be a waste to miss out on the numerous opportunities AM enables; in some instances streamlining work at R&D, decreasing lead-time and costs, enabling novel designs and inventions towards customer, etc.

To fully take advantage of AM an organisation should; discover and exploit possibilities already present today, be aware of future changes and share knowledge internally. However it is not always possible to go all in; investing in every machine, go to every seminar, be a part of every research consortium, share knowledge internally, etc. The future work should be carefully planned out so that it aligns with various interests and make the most out of it.

8 Thesis Contribution

The project shifted focus during the middle of the project as the real problem was identified. It was not about developing a component nor testing some plastic prints. It was realised what VCG really was after were and how to use AM wisely in a holistic perspective, in which the case studies helped but had to a great extent be complemented with theory. The initial plan of the thesis changed a lot with this, but also as our knowledge on AM increased and with some of the hurdles we had during the project. See table 8.1 and 8.2 for the initial planning and the actual workflow.

In this work, the overall flow and content planning was made by Terese Wahlström. The chapters were then subdivided into responsibility areas. Some of the chapters had joint responsibility, namely the data acquisition and the thesis contribution. Johan Sahlström was responsible for the benchmarking, destructive testing and development of a component in metal AM. Wahlström was responsible for the introduction, seven AM process categories, application areas, the ease of post processing test, the modelling of the developed component and the implementation of AM. And due to unforeseen events, Wahlström also had to make all the finishing touches and fixes to the report, and write the chapter on design methodology from scratch.

This thesis does not attempt to be definite. There are more work to be done to bring AM into production and as AM technology gets even more mature for VCG's needs it should be continually investigated. Throughout the thesis we have provided information on future work and areas which we believe are poorly researched.

Through this thesis our hope is that the usefulness of additive manufacturing has been made clearer and that we have provided a good framework to continue the work on bringing AM into production wisely. Whether or not this work easily can be built upon is left for VCG to discover.

Table 8.1 Initial plan.

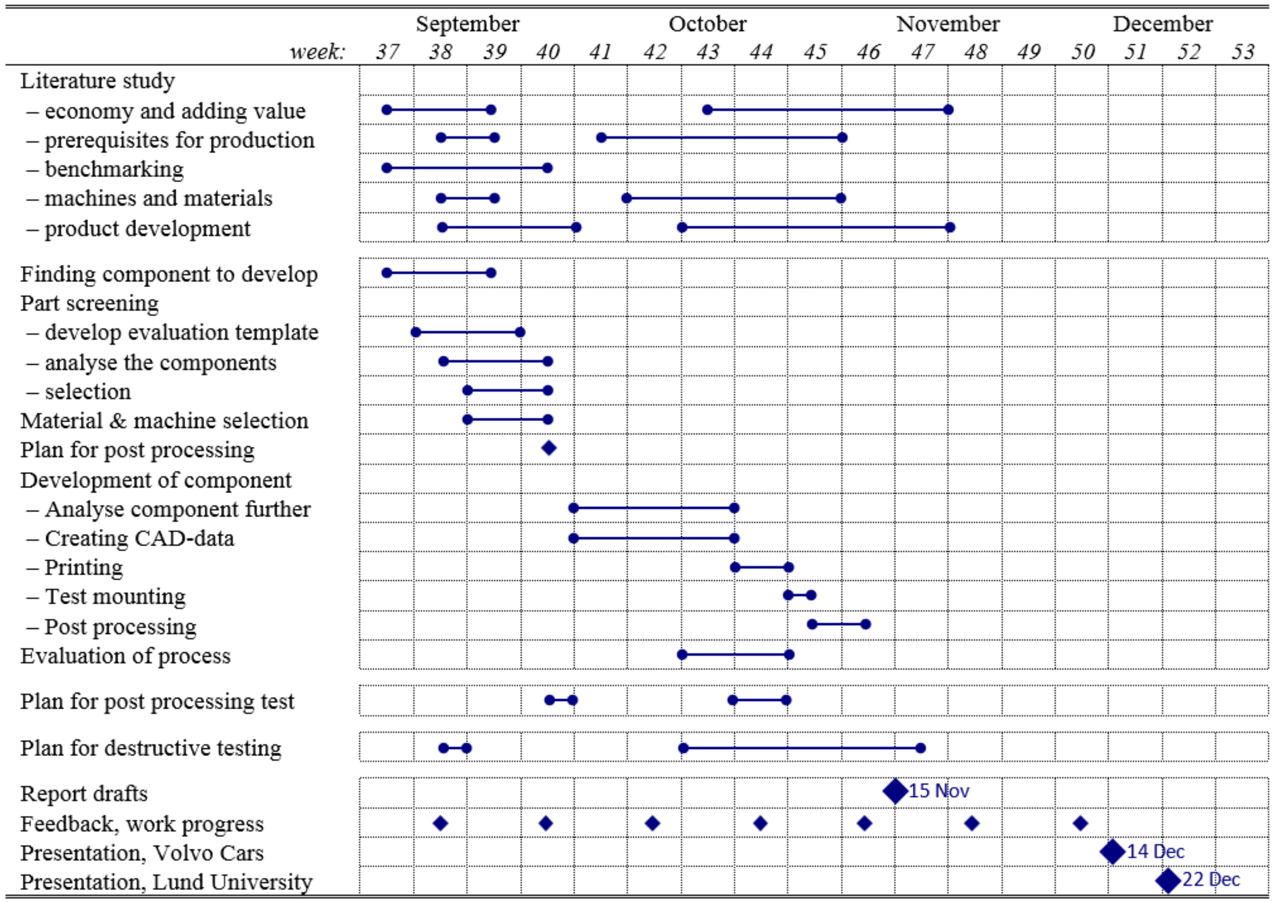
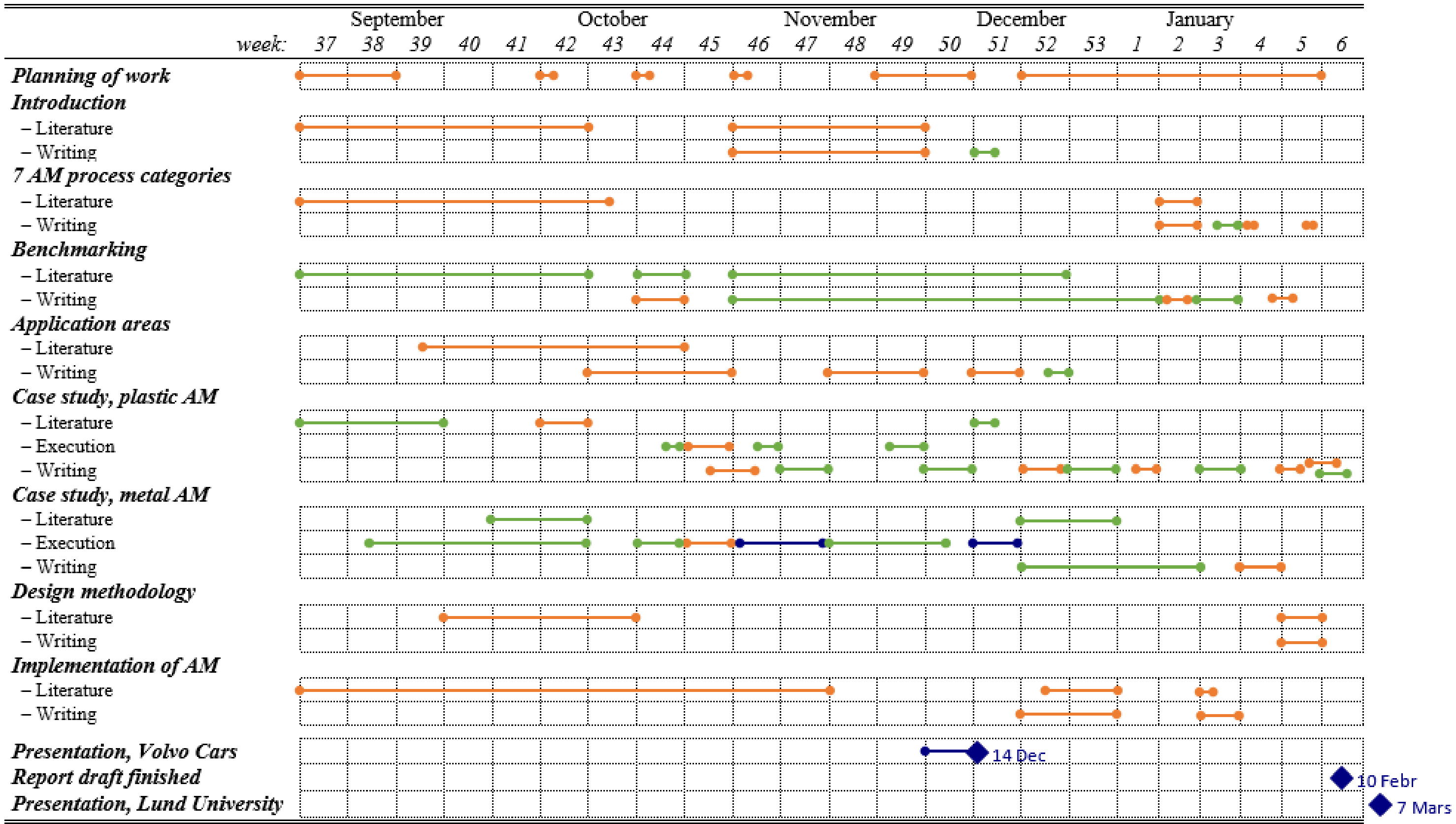


Table 8.2 Actual workflow. Dark blue means teamwork, orange means Wahlström worked and green means Sahlström worked.



References

[1] Heritage. (n.d.). Retrieved January 8, 2016, from www.volvocars.com/intl/about/our-company/heritage

[2] Volvo Car Corporation announces a new brand strategy - "Designed Around You". (2011, August 23). Retrieved January 8, 2016, from www.media.volvocars.com/global/en-gb/media/pressreleases/39763

[3] Core values. (n.d.). Retrieved January 8, 2016, from www.volvocars.com/intl/about/our-company/core-values

[4] Larsson, T. senior principal engineer at Volvo Car Group, Gothenburg, Sweden. Personal conversation (2016, 8 January).

[5] International Organization for Standardization (ISO) & American Society for Testing and Materials (ASTM). (2015). *Additive manufacturing — General principles — Terminology* (ISO/ASTM 52900:2015).

[6] Mellor, S. (2014). *An implementation framework for additive manufacturing.* (PhD dissertation, University of Exeter, United Kingdom). Retrieved December 10, 2015, from https://ore.exeter.ac.uk/repository/bitstream/handle/10871/15036/MellorS.pdf?sequence=1

[7] Zistl, S. (2014) *3D Printing: facts & forecasts.* Retrieved September 8, 2015, from www.siemens.com/innovation/en/home/pictures-of-the-future/industry-and-automation/Additive-manufacturing-facts-and-forecasts.html

[8] Carbon3D introduces CLIP, breakthrough technology for layerless 3D printing. (2015). Retrieved September 8, 2015, from www.carbon3d.com/news/carbon3d-introduces-clip

[9] Schillmoeller, S. (2015, November 18). *25 years of 3D printing at the BMW Group: Pioneers in additive manufacturing methods.* Retrieved December 1, 2015, from www.press.bmwgroup.com/global/pressDetail.html?title=25-years-of-3d-printing-at-the-bmw-group-pioneers-in-additive-manufacturing-methods&outputChannelId=6&id=T0243462EN&left_menu_item=node__5247

[10] Gartner Hype Cycle. (2015). Retrieved November 20, 2015, from www.gartner.com/technology/research/methodologies/hype-cycle.jsp

[11] Flyvbjerg, B. (2006). Five misunderstandings about case-study research. *Qualitative Inquiry, 12*(2), 219-245. Sage Journals. www.dx.doi.org/10.1177/1077800405284363

[12] Reeves, P., vice president of strategic consulting within Stratasys, Derby, United Kingdom. Personal conversation (2015, 15 September).

[13] Gartner, Hype Cycle for 3D Printing, 2015, Michael Shanler, Pete Basiliere 27 July 2015.

[14] Mellor, S. & Hao, L. & Zhang, D. (2014). Additive manufacturing: a framework for implementation *International Journal of Production Economics, 149*(1), 194-201. Elsevier. www.dx.doi.org/10.1016/j.ijpe.2013.07.008

[15] Driscoll, D. & Brizee, A. (n.d.). *What is primary research and how do I get started?* Retrieved September 16, 2015, from https://owl.english.purdue.edu/owl/owlprint/559

[16] O'Leary, D. (2007). Gartner's hype cycle and information system research issues. *International Journal of Accounting Information Systems, 9*(4), 240-252. Elsevier. www.dx.doi.org/10.1016/j.accinf.2008.09.001

[17] Wohler's Associates Inc. (2015). *Wohler's report 2015 - 3D printing and additive manufacturing state of the industry. Annual Worldwide Progress Report.* Wohler's Associates, Colorado, USA.

[18] Gu, D. & Meiners, K. & Wissenbach, K. & Poprawe. (2012). Laser additive manufacturing of metallic components: materials, processes and mechanisms. *International Materials Reviews, 57*(3), 133-164. www.dx.doi.org/10.1179/1743280411Y.0000000014

[19] Huang, S. & Liu, P. & Mokasdar, A. (2012). Additive manufacturing and its societal impact: a literature review. *Advanced Manufacturing Technology, 67(5).* London, United Kingdom: Springer. www.dx.doi.org/10.1007/s00170-012-4558-5

[20] Our common future, chapter 2: towards sustainable development. (1987, August 4). Retrieved January 27, 2016, www.un-documents.net/ocf-02.htm

[21] Burkhart, M. & Aurich, J. (2015). Framework to predict the environmental impact of additive manufacturing in the life cycle of a commercial vehicle. *The 22nd CIRP conference on Life Cycle Engineering*, 408-413. Elsevier. www.dx.doi.org/10.1016/j.procir.2015.02.194

[22] Bourhis, F. & Kerbrat, O. & Dembinski, L. & Jean-Yves, H. & Mognol, P. (2014). Predictive model for environmental assessment in additive manufacturing process. *21st CIRP Conference on Life Cycle Engineering*, 26-31. Elsevier. www.dx.doi.org/10.1016/j.procir.2014.06.031

[23] Kianian, B. & Nopparat, N. (2012). *Resource consumption of additive manufacturing technology* (Master Thesis, Blekinge Institute of Technology, Blekinge, Sweden).

[24] Thomas D. & Gilbert S. (2014). *Costs and cost effectiveness of additive manufacturing.* Applied Economics Office, Engineering Laboratory, U.S. Department of Commerce, USA. Retrieved September 14, 2015, from http://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1176.pdf

[25] Schmid, M. & Levy, G. (2013). *Quality management and estimation of quality costs for additive manufacturing with SLS.* St. Gallen, Switzerland. Retrieved September 28, 2015, from www.iwf.mavt.ethz.ch/ConfiguratorJM/publications/Quality_Ma_133345735583221/p107.pdf

[26] Son, Y. (1990). A cost estimation model for advanced manufacturing systems. *International Journal of Production Research, 29*(3), 441-452. Taylor & Francis Online. www.dx.doi.org/10.1080/00207549108930081

[27] Lindemann, C. & Jahnke, U. & Moi, M. & Koch, R. (2012). *Analyzing product lifecycle costs for a better understanding of cost drivers in additive manufacturing.* Direct Manufacturing Research Center (DMRC) and Chair of Computer Application and Integration in Design and Planning (C.I.K.), The University of Paderborn. Retrieved September 28, 2015, from http://sffsymposium.engr.utexas.edu/Manuscripts/2012/2012-12-Lindemann.pdf

[28] The 7 categories of additive manufacturing. (n.d.). Retrieved September 15, 2015, from www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing

[29] CES EduPack. (2015). Granta Design Ltd (Cambridge, United Kingdom).

[30] ARBURG Plastic Freeforming – boundless freedom. (n.d.). Retrieved January 10, 2016, www.arburg.com/en/products-and-services/additive-manufacturing/apf-process

[31] Molitch, M. (2014, July 16). *Boeing and Lotus F1 team to 3D print carbon reinforced parts.* Retrieved September 16, 2015, from www.3dprintingindustry.com/2014/07/16/boeing-lotus-f1-team-3d-print-carbon-reinforced-parts

[32] Gibson, I. & Rosen, D. & Stucker B. (2010). *Additive Manufacturing technologies, rapid prototyping to direct digital manufacturing.* USA: Springer. www.dx.doi.org/10.1007/978-1-4419-1120-9

[33] Krassenstein, B. (2015). *Carbon3D Unveils Breakthrough CLIP 3D Printing Technology, 25-100X Faster.* Retrieved January 28, 2016, www.3dprint.com/51566/carbon3d-clip-3d-printing

[34] Setterberg, J., task leader at Volvo Car Group, Gothenburg, Sweden. Personal conversation (2015, 13 September).

[35] Feigl, K. (2015, November 5). *Audi Toolmaking prints “Auto Union Typ C”.* Retrieved November 10, 2015, from www.audi-mediacenter.com/en/press-releases/audi-toolmaking-prints-auto-union-typ-c-5095

[36] Bentley Motors, from tires to interiors, Bentley designs with 3D printing. (2013, September). Retrieved September 9, 2015, from www.stratasys.com/resources/case-studies/automotive/bentley-motors#sthash.naDHlhNt.dpuf

[37] History. (2015). Retrieved November 26, 2015, from www.eos.info/about_eos/history

[38] BMW. (2007, September 1). *Rapid prototyping from BMW* [video file]. Retrieved September 14, 2015, from www.bmw.tv/web/com/video.do?videoID=457

[39] BMW USA. (2011, Mars 24). *Inside BMW's Secret "Plant Zero"* [video file]. Retrieved September 9, 2015, from https://youtu.be/5AYPeSyeJB8

[40] Hiemenz, J. (2014, April 4). *3D printing as a manufacturing aid.* Retrieved December 10, 2015 from www.processonline.com.au/content/business/article/3d-printing-as-a-manufacturing-aid-821914319

[41] BMW, manufacturing jigs and fixtures with FDM. (2013, July). Retrieved September 9, 2015, from www.stratasys.com/resources/case-studies/automotive/bmw

[42] FDM thermoplastics. (2015). Retrieved November 26, 2015, from www.stratasys.com/materials/fdm

[43] Schillmoeller, S. (2015, April 29). *Racing technology right from the 3D printer: BMW makes water pump wheel for DTM racecars using additive production method.* Retrieved September 15, 2015, from www.press.bmwgroup.com/global/pressDetail.html?title=racing-technology-right-from-the-3d-printer-bmw-makes-water-pump-wheel-for-dtm-racecars-using&outputChannelId=6&id=T0215062EN&left_menu_item=node__5247

[44] Mearian, L. (2014, June 4). *Inside Ford's 3D Printing Lab, where thousands of parts are made*. Retrieved September 16, 2015, from www.computerworld.com/article/2490192/emerging-technology-inside-ford-s-3d-printing-lab-where-thousands-of-parts-are-made.html

[45] Vanian, J. (2015, June 23) *"Why Ford is partnering with a hot 3D printing start-up".* Retrieved September 8, 2015, from www.fortune.com/2015/06/23/ford-hot-startup-3d-printing

[46] Ford's 3D-Printed Auto Parts Save Millions, Boost Quality. (2013, December 12). Retrieved September 10, 2015, from https://media.ford.com/content/fordmedia/fna/us/en/news/2013/12/12/ford_s-3d-printed-auto-parts-save-millions--boost-quality.pdf

[47] Morey, B. (2009, March 15). *DiMora deploys pattern-less casting technology* Retrieved December 10, 2015, from http://articles.sae.org/6051/

[48] Carbon3D. (2015). Retrieved September 8, 2015, from www.carbon3d.com

[49] Rapidprotovideo. (2011, July 11). *3D rapid prototyping fast tracks GM fuel efficiency gains* [video file]. Retrieved September 14, 2015 from https://youtu.be/R7RmilJYmjo

[50] Rapidprotovideo. (2011, August 11). *3D rapid prototyping enables innovation at General Motors* [video file]. Retrieved September 14, 2015 https://youtu.be/jnkF1_hkT_8

[51] ProJet™ CPX 3000 Teams with Honda Performance Development on their HR28TT engine. (2010). Retrieved December 14, 2015, from www.3dsystems.com/sites/www.3dsystems.com/files/3DS_CS_Honda.pdf

[52] FDM dashboard prototypes holds tight tolerances; improves design. (2013). Retrieved September 11, 2015, from www.stratasys.com/resources/case-studies/automotive/hyundai-mobis

[53] Jaguar Land Rover finds competitive advantage with multi-material 3D Printer. (2013). Retrieved September 9, 2015, from www.stratasys.com/resources/case-studies/automotive/jaguar-land-rover

[54] Dimension 3D printer helps Koenigsegg develop supercar with a torque of 920 Nm. (2013). Retrieved September 9, 2015, from www.stratasys.com/resources/case-studies/automotive/koenigsegg

[55] /Drive. (2014, April 29). *The 3D printed variable turbo /Inside Koenigsegg* [Video file]. Retrieved September 16, 2015 from https://youtu.be/DNedUZxP8NU

[56] Christian von Koenigsegg. (n.d). Retrived January 6, 2016, from www.koenigsegg.com/christian-von-koenigsegg

[57] Okulski, T. (2014, February 2). *The Koenigsegg One:1 is Sweden's 280 mph carbon fiber hypercar*. Retrieved September 16, 2015, from www.jalopnik.com/the-koenigsegg-one-1-is-swedens-280-mph-carbon-fiber-h-1532088783

[58] Koenigsegg One:1. (n.d). Retrived January 6, 2016, from www.koenigsegg.com/one1

[59] Lamborghini speed production workflow with 3D printed production parts. (2015). Retrieved September 9, 2015, from www.stratasys.com/resources/case-studies/automotive/lamborghini-production-parts

[60] Lightweight Components Are Key to Fast Supercar. (2013). Retrieved September 9, 2015, from www.stratasys.com/resources/case-studies/automotive/lamborghini

[61] Kew, O. (2014, August 20) *Interior secrets of next-generation Mercedes S-class.* Retrieved September 8, 2015 from www.autoexpress.co.uk/mercedes/s-class/88314/interior-secrets-of-next-generation-mercedes-s-class

[62] Koslow, T. (2015, September 1). *Peugeot infuses 3D printing into new concept car: The Fractal.* Retrieved September 14, 2015, from www.3dprintingindustry.com/2015/09/01/peugeot-infuses-3d-printing-into-new-concept-car-the-fractal

[63] Belforte, D. (2013, April 30). *Rapid prototyping for mass production of the VW Golf Mark VII.* Retrieved September 11, 2015, from www.industrial-lasers.com/articles/2013/04/rapid-prototyping-for-mass-production-of-the-vw-golf-mark-vii.html

[64] Haur, J. (2015, December 1). *Access Begets Innovation: 3D Printing & Opportunity.* Retrieved January 26, 2016, www.3dprint.com/108148/access-begets-innovation

[65] Sher, D. (2015, June 15). *Gorgeous, modular supercar made possible by 3D printing.* Retrieved September 9, 2015, from www.3dprintingindustry.com/2015/06/24/gorgeous-modular-supercar-made-possible-by-3d-printing

[66] Divergent3D (2015, June 23). *Divergent Microfactories – Blade* [video file]. Retrieved January 26, 2016, www.youtube.com/watch?v=SU7LhQsLthA

[67] Molitch, M. (2013, August 12). R*enishaw contributes 3D printing to the Bloodhound SSC project.* Retrieved September 16, 2015, from www.3dprintingindustry.com/2013/08/12/renishaw-contributes-3d-printing-to-the-bloodhound-ssc-project

[68] Lotus F1 team and 3D Systems move together towards race-ready mass production of parts. Retrieved September 14, 2015, from www.3dsystems.com/learning-center/case-studies/lotus-f1-team-and-3d-systems-move-together-towards-race-ready-mass

[69] Molitch, M. (2015, May 6). *Airbus A350 XWB takes off with over 1000 3D printed parts.* Retrieved September 16, 2015, from www.3dprintingindustry.com/2015/05/06/airbus-a350-xwb-takes-off-with-over-1000-3d-printed-parts

[70] Molitch, M. (2015, June 8). *Preparations begun on mass metal 3D printing of Airbus engine parts.* Retrieved September 17, 2015, from www.3dprintingindustry.com/2015/06/08/preparations-begun-on-mass-metal-3d-printing-of-airbus-engine-parts

[71] Airbus Defence and Space optimizing components using 3D printing for new Eurostar E3000 satellite platforms. (2015, March 19). Retrieved September 21,

2015, from www.airbusdefenceandspace.com/newsroom/news-and-features/airbus-defence-and-space-optimising-components-using-3d-printing-for-new-eurostar-e3000-satellite-platforms

[72] European Space Agency investigates Additive Manufacturing DMP parts for in-space satellite engines. (2015, March). Retrieved September 15, 2015, from www.3dsystems.com/learning-center/case-studies/european-space-agency-investigates-additive-manufacturing-dmp-parts

[73] Kellner, T. (2015, April 14). *The FAA Cleared the First 3D Printed Part to Fly in a Commercial Jet Engine from GE.* Retrieved January 8, 2015, www.gereports.com/post/116402870270/the-faa-cleared-the-first-3d-printed-part-to-fly

[74] Sher, D. (2014, August 11). *3D printed, mass produced parts to give GE's new jet engines an extra boost.* Retrieved September 17, 2015, from www.3dprintingindustry.com/2014/08/11/3d-printing-ge-jet-engine

[75] Szondy, D. (2015, April 19). *GE announces first FAA approved 3D-printed engine part*. Retrieved January 8, 2015, from www.gizmag.com/ge-faa-3d-printing-aircraft-engine-part/37018

[76] Morrison, M. (2015, February 19). *Rolls Royce to fly Trent XWB with largest ever 3D printed part.* Retrieved September 21, 2015, from www.flightglobal.com/news/articles/rolls-royce-to-fly-trent-xwb-with-largest-ever-3d-printed-409207

[77] PolyJet is a game changer for accelerating injection moulded products to market. (2014). Retrieved September 10, 2015, from www.stratasys.com/resources/case-studies/commercial-products/whale

[78] Tooling: Innomia accelerates production and reduces maintenance. (2014). Retrieved September 17, 2015, from www.eos.info/press/case_studies/Innomia

[79] Switching to FDM to build thermoforming moulds reduces cost from $1200 to $100 (2013, June). Retrieved September 10, 2015 from www.stratasys.com/resources/case-studies/commercial-products/xerox-thermoforming

[80] Gartner Press Release, Gartner Says Medical Applications Are Leading Advancement in 3D Printing (2015, August 25). Retrieved November 10, 2015, from www.gartner.com/newsroom/id/3117917

[81] Myler, L. (2013). *3 steps to an irresistible business model.* Retrieved November 2, 2015, from www.forbes.com/sites/larrymyler/2013/08/01/3-steps-to-an-irresistible-business-model-multiple-authentication-methods/

[82] Shanker, A. (2012). What is customer value and how do you deliver it? *Technology Innovation Management Review*, 32-33. Retrieved December 10, 2015, from www.timreview.ca/sites/default/files/article_PDF/Shanker_TIMReview_February2012.pdf

[83] Mavridou, E. & Kehagias, D. & Tzovaras, D. & Hassapis, G. (2011). Mining affective needs of automotive industry customers for building a mass-customization recommender system. *Journal of Intelligent Manufacturing, 24*(2), 251-265. USA: Springer. www.dx.doi.org/10.1007/s10845-011-0579-4

[84] Argandoña, A. (2011). *Stakeholder theory and value creation.* IESE Business School, University of Navarra, Navarra, Spain. Retrieved December 10, 2015, from www.iese.edu/research/pdfs/di-0922-e.pdf

[85] Derry, R. (2012). Reclaiming marginalized stakeholders. *Journal of Business Ethics, 111*(2), 253-264. Netherlands: Springer. www.dx.doi.org/10.1007/s10551-012-1205-x

[86] Bain Brief (2015, July 20). *Five questions to shape a winning 3-D printing strategy.* Retrieved September 17, 2015, from www.bain.com/publications/articles/five-questions-to-shape-a-winning-3d-printing-strategy.aspx/

[87] Conner, B. & Manogharan, G. & Martof, A & Rodomsky, L. & Rodomsky, C. & Jordan, D. & James W. Limperos (2014). Making sense of 3-D printing: creating a map of additive manufacturing products and services. *Additive Manufacturing, 1-4*(1), 64-65. Youngstown State University, United States: Elsevier. www.dx.doi.org/10.1016/j.addma.2014.08.005

[88] Larsson, T., Senior Principal Engineer at Volvo Car Group, Gothenburg, Sweden. Personal conversation (2015, 3 September).

[89] Danjou, S. (2010). *Mehrzieloptimierung der bauteilorientierung für anwendungen der rapid-technologie.* (PhD dissertation, Universität Duisburg-Essen, Duisburg-Essen, Germany).

[90] Eger, T. & Eckert, C. & Clarkson, J. (2005). The role of design freeze in product development. *The 15th International Conference on Engineering Design (ICED'05)*, (pp. 164-165). Melbourne, Australia. Retrieved November 17, 2015, from www.designsociety.org/publication/23137/the_role_of_design_freeze_in_product_development

[91] Republished with permission of Springer Science and Bus Media B V, from CIRP Encyclopedia of Production Engineering, The International Academy for Produ, Laperriere, Luc, Reinhart, Gunther (Eds.), 2014; permission conveyed through Copyright Clearance Center, Inc.

[92] Cheah, C. & Chua, C. & Lee, C. & Feng, C. & Totong, K. (2004). Rapid prototyping and tooling techniques : a review of applications for rapid investment casting. *International Journal of Advanced Manufacturing Technologies, 25(*3), 308-320. London, United Kingdom: Springer-Verlag. www.dx.doi.org/10.1007/s00170-003-1840-6

[93] Hilton, P. & Jacobs, P. (2010). *Rapid tooling technologies and industrial applications*. New York, USA: Marcel Dekker Inc.

[94] Wang, W. & Stoll, H. & Conley, J. (2009). *Rapid tooling guidelines for sand casting.* New York: Springer.

[95] Saunders, M. (2016, January 4) *Conformal-cooled mould tools - how to cut cycle times and boost part quality.* Retrieved January 5, 2015, www.linkedin.com/pulse/conformal-cooled-mould-tools-how-cut-cycle-times-boost-saunders

[96] Weiss, F. & Binz, H. & Roth, D. (2015). Approach to consider rapid manufacturing in the early phases of product development. *Proceedings of the 20th International*

Conference on Engineering Design (ICED 15) Vol 4: Design for X, Design to X, Milan, Italy.

[97] Leutenecker, B. & Klahn, C. & Meboldt, M. (2015). Indicators and design strategies for direct part production by additive manufacturing. *Proceedings of the 20th International Conference on Engineering Design (ICED 15) Vol 4: Design for X, Design to X, Milan, Italy.*

[98] Weller, C. & Kleer, R. & Piller, F. (2015). Economic implications of 3D printing: market structure models in light of additive manufacturing revisited. *International Journal of Production Economics, 164(1)*, 43-56. Elsevier. www.dx.doi.org/10.1016/j.ijpe.2015.02.020

[99] Solutions across applications (n.d.). Retrieved December 26, 2015, from www.stratasysdirect.com/applications

[100] Achillas, C. & Aidonis, D. & Iakovou, E. & Thymianidis, M. & Tzetzis, D. (2015). A methodological framework for the inclusion of modern additive manufacturing into the production portfolio of a focused factory. *International Journal of Production Economics, 149*(1), 328-339. Elsevier. www.dx.doi.org/10.1016/j.jmsy.2014.07.014

[101] Yang, S. & Zhao, Y. (2015). Additive manufacturing-enabled design theory and methodology: a critical review. *The International Journal of Advanced Manufacturing Technology, 80*(1), 327-342. London, United Kingdom: Springer. www.dx.doi.org/10.1007/s00170-015-6994-5

[102] Lindemann, C. & Reiher, T. & Jahnke, U. & Koch, R. (2015). Towards a sustainable and economic selection of part candidates for additive manufacturing. *Rapid Prototyping Journal, 21*(2), 216-227. Emerald Insight. www.dx.doi.org/10.1108/RPJ-12-2014-0179

[103] Rosen, D. (2014). Research supporting principles for design for additive manufacturing. *Virtual and Physical Prototyping, 9*(4), 225-232. Taylor & Francis. www.dx.doi.org/10.1080/17452759.2014.951530

[104] Danjou, S. & Koehler, P. (2008). *Bridging the Gap between CAD and Rapid Technologies.* Châtenay-Malabry: Ecole Centrale Paris.

[105] PicoPrint 3D Printer. (n.d.). Retrieved January 28, 2016, https://apollo.open-resource.org/mission:resources:picoprint

[106] What is 3MF? (n.d.). Retrieved January 28, 2016, www.3mf.io/what-is-3mf

[107] Elner-Haglund, K., lecturer at the Division of Machine Design, Department of Design Sciences LTH, Lund University, Lund, Sweden. Mail exchange (2015, 17 October).

[108] Fortus Finishing Touch Smoothing Station (n.d.). Retrieved December 10, 2015, from www.stratasys.com/3d-printers/~/media/E6CF0D673FA54E509B11F7B7F82055A4.ashx

[109] Windform. (n.d.). Retrived January 6, 2016, www.windform.com

[110] Windform XT 2.0 (n.d.). Retrived January 6, 2016, www.windform.com/PDF/SCHEDA_WF_XT_2_0_ENG.pdf

[111] SLM® metal powder. (n.d.). Retrived January 6, 2016, http://stage.slm-solutions.com/download.php?f=c714ab082c7d7a5992b2f0b7cd74c720

[112] Titanium Ti-6Al-4V (Grade 5), Annealed. (n.d.). Retrived January 6, 2016, from www.matweb.com/search/DataSheet.aspx?MatGUID=a0655d261898456b958e5f825ae85390

[113] Quality in all we do. (n.d.). Retrived September 21, 2015, from www.materialise.com/quality-in-all-we-do

[114] Maropoulos, P. & Ceglarek, D. (2010). Design verification and validation in product lifecycle. *CIRP Annals - Manufacturing Technology, 59*(2), 740-759. Elsevier. www.dx.doi.org/10.1016/j.cirp.2010.05.005

[115] Additive Manufacturing: SASAM Standardisation Roadmap (2015). Support Action for Standardisation in Additive Manufacturing. Retrieved January 26, 2016, www.sasam.eu

[116] Reprinted from International Journal of Production Economics, Vol 149 /1, Mellor, S. & Hao, L. & Zhang, D., Additive manufacturing: a framework for implementation, p. 196, Copyright (2014), with permission from Elsevier.

[117] Nickerson, J. & Silverman, B. & Zenger T. (2007). *The 'problem' of creating and capturing value.* Retrieved November 17, 2015, from http://apps.olin.wustl.edu/faculty/nickerson/creatingandcapturingvalue.pdf

[118] Nationalencyklopedin (n.d.). *Facit AB.* Retrieved January 25, 2016, www.ne.se/uppslagsverk/encyklopedi/l%C3%A5ng/facit-ab

[119] Creating value and capturing value. (2003). [PowerPoint slides] Sam Houston State University, USA. Retrieved November 16, 2015, from www.shsu.edu/dpg006/ECON%205333.day8.ppt

[120] Farzin, Y. & Huisman, K. & Kort, P. (1998). Optimal timing of technology adoption. *Journal of Economic Dynamics & Control, 22*(5), 779-799. Elsevier. www.dx.doi.org/10.1016/S0165-1889(97)00097-3

[121] Vecchiato, R. (2014). Creating value through foresight: first mover advantages and strategic agility. *Technological Forecasting & Social Change, 101,* 25-36. Elsevier. www.dx.doi.org/10.1016/j.techfore.2014.08.016

[122] Hill, A. & Hill, T. (2009). *Manufacturing operations strategy, texts and cases.* 3rd ed. Basingstoke: Palgrave Macmillan.

[123] Polymera material kompendium. (2003). Luleå, Sweden: Institution of Physics, department of Material Science and Engineering, Luleå Technical University.

Disclaimer:

All statements in this report attributable to Gartner represent Terese Wahlström' s interpretation of data, research opinion or viewpoints published as part of a syndicated subscription service by Gartner, Inc., and have not been reviewed by Gartner. Each Gartner publication speaks as of its original publication date (and not as of the date of this master thesis). The opinions expressed in Gartner publications are not representations of fact, and are subject to change without notice.

Appendix A Collected Data

A.1 Test on Plastic AM Components

Two test on plastic prints on production machines and materials were conducted. The tensile test specimen was named *A* and *AB*, the Izod impact test specimen was named *B*, and the geometrically advanced component were named C.

Every test was given a test identification. Also each machine manufacturer, machine and material was given and separate identification numbers. The test involved in total three machine suppliers, five different machines and twelve different materials, which are summarised in table A1.1.

Table A1.1 Identification for the tests.

Test ID	*ID Machine*	*ID Material*	*Layer thickness*
1	1.	1.	0.178mm
2	1.	2.	0.127mm
3	1.	3.	0.127mm
4	1.	4.	0.127mm
5	2.	5.	0.12mm
6	3.	5.	0.12mm
7	3.	6.	0.12mm
8	3.	7.	0.12mm
9	4.	8.	0.12mm
10	4.	9.	0.12mm
11	4.	10.	0.12mm
12	4.	11.	0.12mm
13	5.	12.	0.032mm
14	6.	13.	0.16mm
15	6.	14.	0.16mm

A.1.1 Destructive Testing

Two destructive tests were conducted, tensile and Izod impact strength. The destructive testing was done according to the standards, ASTM D638 and ASTM D526. The drawings of these can be found in figure A1.1 and A1.2.

When the CAD-data was made, the tensile test specimen was mistakenly made with two indents symmetrically placed along the length of the test body on one side, as illustrated by figure A1.1. According to the standard, these was only intended to be reference marks put in afterwards, in the drawing named Gauge marks. A few of the specimens was therefore ordered extra without the indents, these were named *AB* and the ones with the indents were named *A*.

The test specimens can be seen mounted in their respective test machine, as seen in figure A1.4 and A1.5.

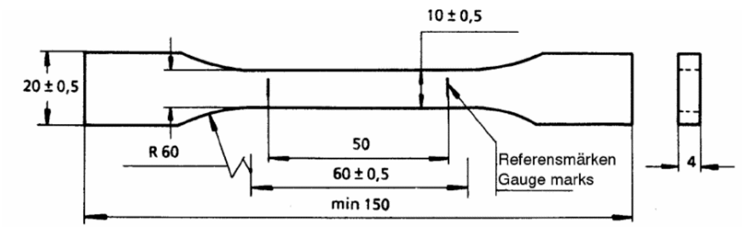


Figure A1.1 Test specimen for tensile strength named A, all dimensions in mm.

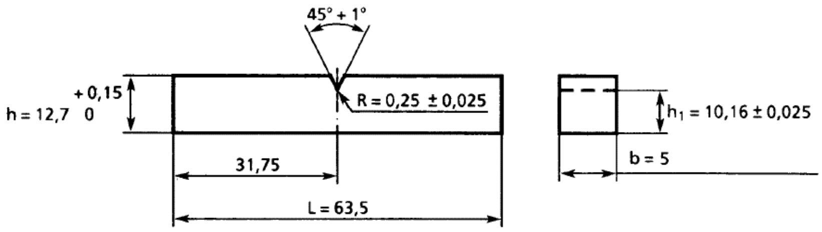


Figure A1.2 Test specimen for Izod impact strength named B, all dimensions in mm.

Further, the different orientations added an extra number to the name of the specimen depending on if it was orientated on its edge, flat or upright in the machine. See figure A1.3.

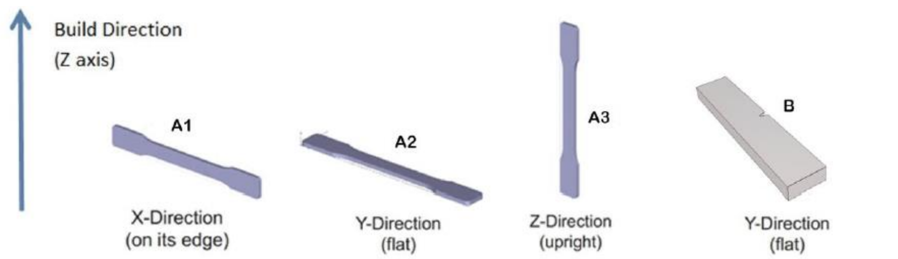


Figure A1.3 Build orientation of the test specimens. Rotation along the xy-plane is allowed, as long as the Z-axis do not change.

The result of the tensile strength test can be found in table A1.3 to A1.7 and the result of the Izod impact strength test can be found in table A1.8 and A1.9.

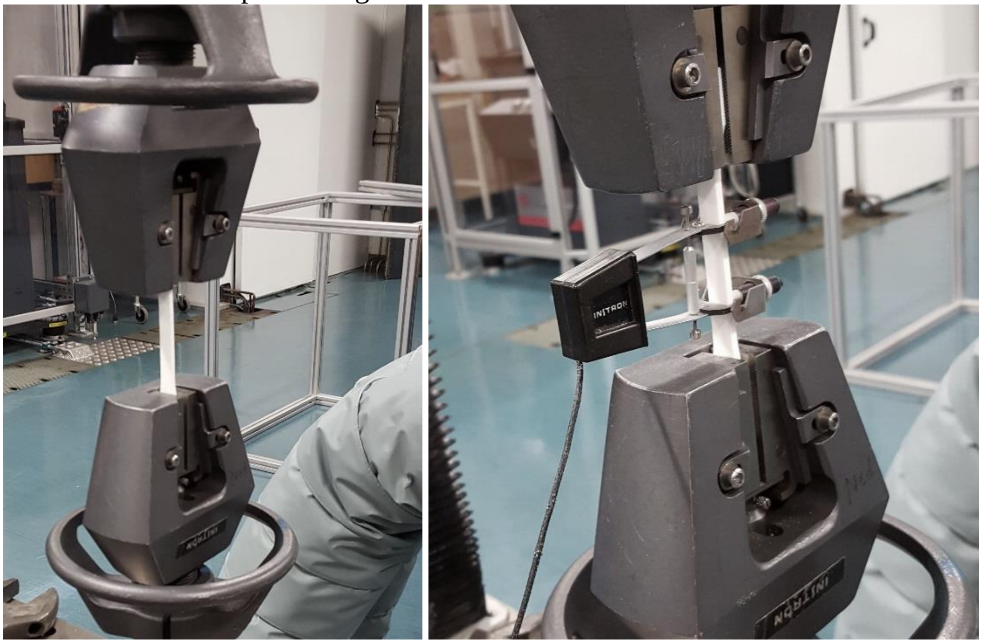


Figure A1.4 Tensile test specimen in machine prior to testing, with and without extensometer.

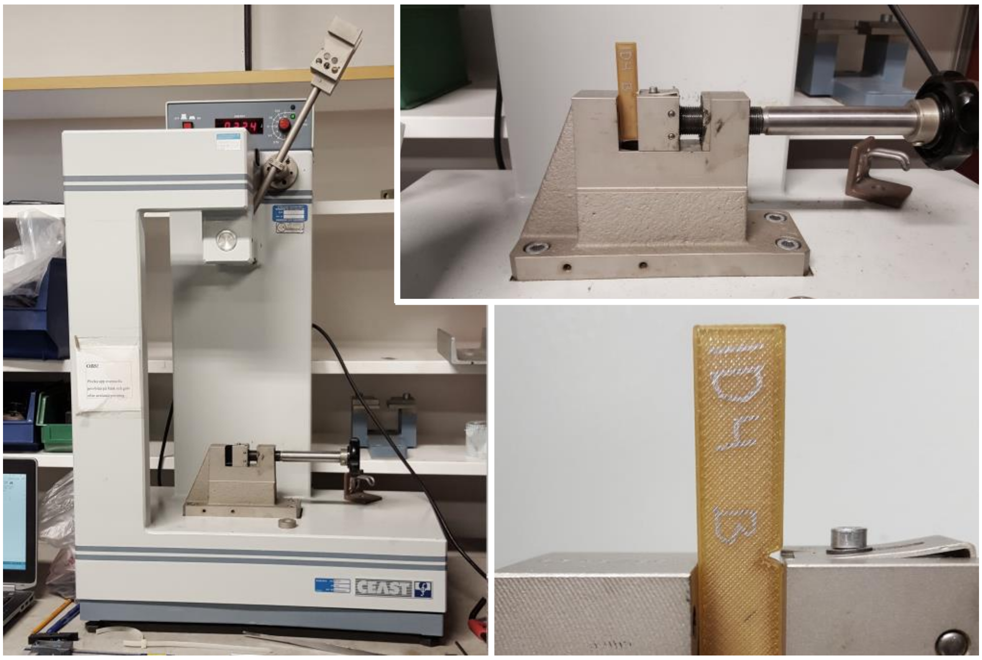


Figure A1.5 The Izod test machine and a sample mounted in the machine prior to testing. Note how the notch in the sample is mounted towards the pendulum.

A.1.1.1 Calculations of Material Properties and Results

To obtain the result from the destructive testing it is necessary to calculate some of the properties from the measurements attained. These are calculated according to equation A1.1 to A1.5.

Tensile strength at yield and break, σ is calculated from the equation A1.1, were F is the tensile force, w is the width of the test specimen and t is the thickness of the test specimen.

$$\sigma = \frac{F}{A_0} = \frac{F}{w \cdot t} = \left[\frac{N}{mm^2}\right] \tag{A1.1}$$

Strain, ε, is calculated from the equation A1.2, were l_1 is the gauge length of the unloaded test specimen and l_2 is the gauge length of the loaded test specimen.

$$\varepsilon = \frac{l_2 - l_1}{l_1} = [\%] \tag{A1.2}$$

The tensile modulus, E, can be calculated from the equation A1.3 after the point of yield has been decided with its associated tensile strength and strain.

$$E = \frac{\sigma_y}{\varepsilon_y} = \left[\frac{N}{mm^2}\right] \tag{A1.3}$$

Impact strength, A, expressed as energy absorbed per unit cross-sectional area is calculated from the equation A1.4, were W is the energy absorbed by the test specimen and h_1 is the height of the test piece to base of notch as shown in figure A1.2.

$$A = \frac{W}{A_0} = \frac{W}{w \cdot h_1} = \left[\frac{J}{mm^2}\right] \tag{A1.4}$$

Impact strength, B, expressed as energy absorbed per unit thickness is calculated from equation A1.5.

$$B = \frac{W}{w} = \left[\frac{J}{mm}\right] \tag{A1.5}$$

Table A1.3 Tensile strength test results.

Test piece	*Width (mm)*	*Thickness (mm)*	*Initial length (mm)*	*Peak load (N)*	*Tensile strength, yield (MPa)*	*Tensile strength, ultimate (MPa)*	*Tensile modulus (MPa)*	*Elongation at yield (%)*	*Elongation at break (%)*
ID1 A1 bit2	9.99	4.00	29.003	1883.04	32.20	47.10	2034.60	1.58	3.04
ID1 A1 bit3	9.98	4.03	29.443	1887.77	31.60	46.90	2027.30	1.56	2.10
ID1 A1 bit4	10.07	4.05	27.030	1890.10	29.80	46.30	1961.40	1.52	2.90
ID1 A1 bit5	10.00	4.00	27.180	1884.19	25.80	47.10	2347.10	1.10	3.09
ID1 A1 bit6	9.99	4.01	28.035	1877.98	31.60	46.90	2103.80	1.50	3.19
Average					30.20	46.86	2094.84	1.45	2.86
Tech Spec					**32.00**	**46.00**	**1282.00**	**2.40**	**30.00**
Difference					**-1.80**	**0.86**	**812.84**	**-0.95**	**-27.14**
ID1 A2 bit1	10.00	4.25	26.602	1777.26	26.40	41.80	2152.50	1.23	3.53
ID1 A2 bit2	9.95	4.26	29.704	1780.12	29.00	42.00	1872.60	1.55	3.46
ID1 A2 bit3	9.98	4.26	26.582	1821.94	29.10	42.90	2007.60	1.45	3.73
Average					28.17	42.23	2010.90	1.41	3.57
Tech Spec					**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Difference					-	-	-	-	-
ID1 A3 bit1	10.11	4.16	25.255	1119.05	16.50	26.60	1893.70	0.87	1.49
ID1 A3 bit2	10.06	4.13	29.221	1115.93	20.50	26.90	1760.50	1.17	1.68
ID1 A3 bit3	10.14	4.15	27.908	974.70	20.40	23.20	1760.00	1.16	1.36
Average					19.13	25.57	1804.73	1.07	1.51
Tech Spec					**28.00**	**38.50**	**1138.00**	**2.70**	**5.40**
Difference					**-8.87**	**-12.93**	**666.73**	**-1.63**	**-3.89**
ID2 A1 bit1	10.10	3.98	27.429	1400.93	26.60	34.90	3377.90	0.79	1.17
ID2 A1 bit2	10.09	3.99	27.087	1372.18	28.10	34.10	3449.90	0.82	1.08
ID2 A1 bit3	10.09	4.00	27.808	1354.79	27.20	33.60	3246.30	0.84	1.23
Average					27.30	34.20	3358.03	0.82	1.16
Tech Spec					**29.00**	**33.00**	**2010.00**	**2.00**	**9.00**
Difference					**-1.70**	**1.20**	**1348.03**	**-1.18**	**-7.84**

Table A1.4 Tensile strength test results.

Test piece	*Width (mm)*	*Thickness (mm)*	*Initial length (mm)*	*Peak load (N)*	*Tensile strength, yield (MPa)*	*Tensile strength, ultimate (MPa)*	*Tensile modulus (MPa)*	*Elongation at yield (%)*	*Elongation at break (%)*
ID3 A1 bit1	10.07	3.98	27.814	1252.91	26.10	31.30	3517.40	0.74	1.08
ID3 A1 bit2	10.07	3.99	27.641	1241.11	26.90	30.90	3407.20	0.79	1.10
ID3 A1 bit3	10.05	3.98	28.017	1286.69	26.40	32.20	3567.90	0.74	1.17
Average					26.47	31.47	3497.50	0.76	1.12
Tech Spec					**31.00**	**32.00**	**2230.00**	**2.00**	**7.00**
Difference					**-4.53**	**-0.53**	**1267.50**	**-1.24**	**-5.88**
ID4 A1 bit1	10.17	4.04	27.701	3375.38	35.30	82.20	4945.20	0.71	2.28
ID4 A1 bit2	10.17	4.04	27.943	3252.51	51.60	79.20	6012.90	0.86	1.70
ID4 A1 bit3	10.18	4.04	27.552	3374.79	50.10	82.10	4774.50	1.05	2.12
Average					45.67	81.17	5244.20	0.87	2.03
Tech Spec					**64.00**	**81.00**	**2770.00**	**2.20**	**3.30**
Difference					**-18.33**	**0.17**	**2474.20**	**-1.33**	**-1.27**
ID5 A1 bit1	10.05	3.88	27.376	1516.70	21.00	38.90	2836.20	0.74	2.49
ID5 A1 bit2	10.07	3.94	27.304	1572.92	16.80	39.60	3037.60	0.55	2.52
ID5 A1 bit3	10.06	3.92	27.448	1596.40	23.20	40.50	2888.80	0.80	2.75
Average					20.33	39.67	2920.87	0.70	2.59
Tech Spec					**N/A**	**48.00**	**1700.00**	**N/A**	**15.00**
Difference					-	**-8.33**	**1220.87**	-	**-12.41**
ID5 A2 bit1	9.96	4.16	27.438	1738.36	28.00	42.00	2694.90	1.04	2.70
ID5 A2 bit2	9.93	4.17	27.904	1745.66	22.40	42.40	3114.60	0.72	2.57
ID5 A2 bit3	9.99	4.16	27.180	1837.86	25.50	44.20	2932.30	0.87	3.25
Average					25.30	42.87	2913.93	0.88	2.84
Tech Spec					**N/A**	**48.00**	**1700.00**	**N/A**	**15.00**
Difference					-	**-5.13**	**1213.93**	-	**-12.16**
ID5 A3 bit1	9.90	3.93	27.037	1187.85	23.10	30.50	2940.60	0.78	1.15
ID5 A3 bit2	9.92	3.93	27.160	1197.56	22.10	30.70	2950.70	0.75	1.18
ID5 A3 bit3	9.93	3.90	27.287	1215.84	21.90	31.40	2731.50	0.80	1.44
Average					22.37	30.87	2874.27	0.78	1.26
Tech Spec					**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Difference					-	-	-	-	-

Table A1.5: Tensile strength test results.

Test piece	*Width (mm)*	*Thickness (mm)*	*Initial length (mm)*	*Peak load (N)*	*Tensile strength, yield (MPa)*	*Tensile strength, ultimate (MPa)*	*Tensile modulus (MPa)*	*Elongation at yield (%)*	*Elongation at break (%)*
ID5 AB1 bit1	10.10	3.93	28.075	1828.39	25.30	46.10	2785.90	0.91	8.48
ID5 AB1 bit2	10.07	3.90	27.203	1776.50	26.70	45.20	2789.30	0.96	7.71
ID5 AB1 bit3	10.09	3.92	27.744	1826.42	28.70	46.20	2758.00	1.04	8.02
Average					26.90	45.83	2777.73	0.97	8.07
Tech Spec					**N/A**	**48.00**	**1700.00**	**N/A**	**15.00**
Difference					-	**-2.17**	**1077.73**	-	**-6.93**
ID5 AB2 bit1	9.91	4.17	27.919	1972.44	22.40	47.70	2973.60	0.75	9.18
ID5 AB2 bit2	9.96	4.12	27.221	1934.02	27.10	47.10	3007.00	0.90	9.48
ID5 AB2 bit3	9.95	4.21	27.970	1961.91	19.90	46.80	3030.50	0.66	7.38
Average					23.13	47.20	3003.70	0.77	8.68
Tech Spec					**N/A**	**48.00**	**1700.00**	**N/A**	**15.00**
Difference					-	**-0.80**	**1303.70**	-	**-6.32**
ID5 AB3 bit1	9.93	3.95	26.767	1416.78	23.00	36.10	2925.30	0.78	1.76
ID5 AB3 bit2	9.93	3.95	26.816	1252.25	19.10	31.90	2884.50	0.66	1.43
ID5 AB3 bit3	9.85	3.90	27.411	1138.83	18.90	29.60	2680.80	0.70	1.37
Average					20.33	32.53	2830.20	0.71	1.52
Tech Spec					**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Difference					-	-	-	-	-
ID6 A1 bit1	10.30	4.11	27.686	1731.82	24.50	40.90	2313.60	1.06	5.04
ID6 A1 bit2	10.29	4.03	27.523	1706.55	24.30	41.20	2528.60	0.96	4.72
ID6 A1 bit3	10.26	3.94	26.605	1683.50	24.20	41.60	2495.10	0.97	4.65
Average					24.33	41.23	2445.77	1.00	4.80
Tech Spec					**N/A**	**48.00**	**1700.00**	**N/A**	**15.00**
Difference					-	**-6.77**	**745.77**	-	**-10.20**
ID6 A2 bit1	10.11	4.21	27.003	1824.99	23.00	42.90	2677.40	0.86	5.55
ID6 A2 bit2	10.14	4.26	27.674	1915.13	25.80	44.30	2832.10	0.91	14.16
ID6 A2 bit3	10.11	4.23	28.196	1925.51	27.60	45.00	2531.40	1.09	10.42
Average					25.47	44.07	2680.30	0.95	10.04
Tech Spec					**N/A**	**48.00**	**1700.00**	**N/A**	**15.00**
Difference					-	**-3.93**	**980.30**	-	**-4.96**

Table A1.6 Tensile strength test results.

Test piece	*Width (mm)*	*Thickness (mm)*	*Initial length (mm)*	*Peak load (N)*	*Tensile strength, yield (MPa)*	*Tensile strength, ultimate (MPa)*	*Tensile modulus (MPa)*	*Elongation at yield (%)*	*Elongation at break (%)*
ID6 A3 bit1	9.96	4.01	26.956	1691.15	19.60	42.30	2835.70	0.69	4.13
ID6 A3 bit2	9.99	3.97	28.318	1685.19	24.70	42.50	2491.20	0.99	4.50
ID6 A3 bit3	9.99	3.96	27.793	1663.98	25.10	42.10	2857.10	0.88	4.11
Average					23.13	42.30	2728.00	0.85	4.25
Tech Spec					**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Difference					-	-	-	-	-
ID7 A1 bit1	10.31	3.96	26.942	1384.36	16.00	33.90	5835.60	0.27	1.55
ID7 A1 bit2	10.29	3.97	28.772	1407.69	16.10	34.50	5645.60	0.28	1.48
ID7 A1 bit3	10.28	3.96	26.875	1374.63	16.10	33.80	5027.30	0.32	1.49
Average					16.07	34.07	5502.83	0.29	1.51
Tech Spec					**N/A**	**51.00**	**3200.00**	**N/A**	**9.00**
Difference					-	**-16.93**	**2302.83**	-	**-7.49**
ID8 A1 bit1	10.03	3.99	28.463	1860.67	31.70	46.50	2231.00	1.42	17.31
ID8 A1 bit2	10.01	3.95	27.155	1871.01	33.20	47.30	2139.40	1.55	18.38
ID8 A1 bit3	10.01	3.97	26.343	1871.39	33.40	47.10	2322.90	1.44	17.93
Average					32.77	46.97	2231.10	1.47	17.87
Tech Spec					**N/A**	**48.00**	**1600.00**	**N/A**	**45.00**
Difference					-	**-1.03**	**631.10**	-	**-27.13**
ID9 A1 bit1	9.89	3.90	27.986	1385.28	20.30	35.90	2981.70	0.68	2.19
ID9 A1 bit2	9.98	4.09	26.667	1515.63	19.20	37.10	3083.90	0.62	2.23
ID9 A1 bit3	9.93	3.99	27.570	1411.60	25.80	35.60	2343.60	1.10	2.24
Average					21.77	36.20	2803.07	0.80	2.22
Tech Spec					**N/A**	**43.00**	**1586.00**	**N/A**	**14.00**
Difference					-	**-6.80**	**1217.07**	-	**-11.78**
ID9 A2 bit1	9.85	3.90	26.880	1468.37	25.90	38.20	2997.70	0.86	2.18
ID9 A2 bit2	9.87	3.95	27.754	1476.47	24.00	37.90	2879.60	0.83	2.35
ID9 A2 bit3	9.90	3.95	26.662	1428.70	23.40	36.50	3194.00	0.73	2.00
Average					24.43	37.53	3023.77	0.81	2.18
Tech Spec					**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Difference					-	-	-	-	-

Table A1.7 Tensile strength test results.

Test piece	*Width (mm)*	*Thickness (mm)*	*Initial length (mm)*	*Peak load (N)*	*Tensile strength, yield (MPa)*	*Tensile strength, ultimate (MPa)*	*Tensile modulus (MPa)*	*Elongation at yield (%)*	*Elongation at break (%)*
ID9 A3 bit1	9.84	3.90	27.164	534.31	11.70	13.90	2244.60	0.52	0.64
ID9 A3 bit2	9.90	4.00	27.785	1100.45	18.60	27.80	2227.40	0.83	1.71
ID9 A3 bit3	9.89	3.98	27.693	892.25	14.10	22.70	2961.30	0.48	1.05
Average					14.80	21.47	2477.77	0.61	1.13
Tech Spec					**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Difference					-	-	-	-	-
ID10 A1 bit1	10.22	4.32	27.216	1005.85	10.50	22.80	4400.40	0.24	5.02
ID10 A1 bit2	10.22	4.36	27.928	996.79	10.70	22.40	4084.30	0.26	5.21
ID10 A1 bit3	10.21	4.33	26.985	1011.66	11.00	22.90	4313.40	0.26	4.33
Average					10.73	22.70	4266.03	0.25	4.85
Tech Spec					**27.00**	**26.00**	**4068.00**	**1.40**	**1.40**
Difference					**-16.27**	**-3.30**	**198.03**	**-1.15**	**3.45**
ID11 A1 bit1	9.78	4.01	26.838	1238.83	13.90	31.60	2008.50	0.69	7.76
ID11 A1 bit2	9.83	4.02	27.666	1187.42	15.40	30.00	1846.50	0.83	6.56
ID11 A1 bit3	9.83	4.03	26.217	1206.56	15.20	30.50	1814.20	0.84	7.80
Average					14.83	30.70	1889.73	0.79	7.37
Tech Spec					**37.00**	**48.00**	**1517.00**	**5.00**	**47.00**
Difference					**-22.17**	**-17.30**	**372.73**	**-4.21**	**-39.63**
ID12 A1 bit1	10.23	4.36	27.258	1637.94	29.10	36.70	3797.80	0.77	14.23
ID12 A1 bit2	10.20	4.33	27.232	1611.51	29.60	36.50	3889.50	0.76	15.86
ID12 A1 bit3	10.19	4.36	27.299	1645.71	29.40	37.00	3530.00	0.83	14.63
Average					29.37	36.73	3739.10	0.79	14.91
Tech Spec					**N/A**	**56.21**	**3289.80**	**N/A**	**14.82**
Difference					-	**-19.48**	**449.30**	-	**0.09**
ID13 A1 bit1	10.01	3.93	25.946	1009.27	20.00	25.70	3353.90	0.60	0.82
ID13 A1 bit2	10.03	4.07	27.381	1058.91	18.70	25.90	2682.60	0.70	1.11
ID13 A1 bit3	10.03	3.91	26.730	1125.19	21.70	28.70	3448.90	0.63	0.94
Average					20.13	26.77	3161.80	0.64	0.96
Tech Spec					**N/A**	**49.00**	**2168.00**	**N/A**	**8.30**
Difference					-	**-22.23**	**993.80**	-	**-7.34**

Table A1.8 Tensile strength test results.

Test piece	*Width (mm)*	*Thickness (mm)*	*Initial length (mm)*	*Peak load (N)*	*Tensile strength, yield (MPa)*	*Tensile strength, ultimate (MPa)*	*Tensile modulus (MPa)*	*Elongation at yield (%)*	*Elongation at break (%)*
ID14 A1 bit1	10.04	4.06	27.229	1688.93	41.40	41.40	4161.70	1.05	1.05
ID14 A1 bit2	10.07	4.06	27.931	1828.63	35.00	44.70	4381.20	0.80	1.15
Average					38.20	43.05	4271.45	0.93	1.10
Tech Spec					**N/A**	**57.50**	**2500.00**	**N/A**	**17.50**
Difference					-	**-14.45**	**1771.45**	-	**-16.40**
ID14 A2 bit1	10.10	4.00	27.568	2084.75	35.70	51.60	3006.20	1.19	3.16
ID14 A2 bit2	10.10	4.00	27.218	2096.32	40.00	51.90	3349.70	1.19	3.87
ID14 A2 bit3	10.09	4.00	27.500	1998.19	36.20	49.50	3521.20	1.03	3.09
Average					37.30	51.00	3292.37	1.14	3.37
Tech Spec					**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Difference					-	-	-	-	-
ID14 AB1 bit1	10.00	4.04	27.059	2300.03	37.20	56.90	4113.30	0.91	3.12
ID14 AB1 bit2	10.00	4.03	27.975	2286.90	35.20	56.70	4433.00	0.79	3.07
ID14 AB1 bit3	9.99	4.03	27.672	2313.84	32.40	57.50	4569.00	0.71	2.98
Average					34.93	57.03	4371.77	0.80	3.06
Tech Spec					**N/A**	**57.50**	**2500.00**	**N/A**	**17.50**
Difference					-	**-0.47**	**1871.77**	-	**-14.44**
ID14 AB2 bit1	10.05	3.98	27.856	2216.44	39.00	55.40	3409.00	1.15	3.39
ID14 AB2 bit2	10.05	3.98	28.789	2256.90	37.90	56.40	3816.70	0.99	3.01
ID14 AB2 bit3	10.07	3.97	27.524	2261.70	37.30	56.60	4106.10	0.91	3.74
Average					38.07	56.13	3777.27	1.02	3.38
Tech Spec					**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Difference					-	-	-	-	-
ID15 A1 bit1	10.06	4.06	26.605	1605.51	24.40	39.30	3135.50	0.78	1.79
ID15 A1 bit2	10.07	4.06	26.225	1601.06	27.10	39.20	2724.10	1.00	1.98
ID15 A1 bit3	10.09	4.06	28.805	1587.99	24.30	38.80	2863.90	0.85	1.81
Average					25.27	39.10	2907.83	0.88	1.86
Tech Spec					**N/A**	**42.50**	**1900.00**	**N/A**	**27.50**
Difference					-	**-3.40**	**1007.83**	-	**-25.64**

Table A1.9 Tensile strength test results.

Test piece	*Width (mm)*	*Thickness (mm)*	*Initial length (mm)*	*Peak load (N)*	*Tensile strength, yield (MPa)*	*Tensile strength, ultimate (MPa)*	*Tensile modulus (MPa)*	*Elongation at yield (%)*	*Elongation at break (%)*
ID15 A2 bit1	10.06	3.99	27.828	1454.92	23.60	36.20	2452.90	0.96	2.63
ID15 A2 bit2	10.06	3.98	27.966	1536.29	19.60	38.40	4813.90	0.41	1.42
ID15 A2 bit3	10.06	3.98	28.116	1487.62	18.90	37.20	5062.00	0.37	1.42
Average					20.70	37.27	4109.60	0.58	1.82
Tech Spec					**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Difference					-	-	-	-	-
ID15 AB1 bit1	10.06	4.05	28.489	1647.82	28.40	40.40	5154.80	0.55	4.27
ID15 AB1 bit2	10.11	4.06	27.553	1625.12	25.30	39.60	5357.20	0.47	2.85
ID15 AB1 bit3	10.08	4.03	28.209	1618.05	29.40	39.80	4292.50	0.68	8.47
Average					27.70	39.93	4934.83	0.57	5.20
Tech Spec					**N/A**	**42.50**	**1900.00**	**N/A**	**27.50**
Difference					-	**-2.57**	**3034.83**	-	**-22.30**
ID15 AB2 bit1	10.06	3.99	27.975	1484.58	30.60	37.00	3326.10	0.92	9.07
ID15 AB2 bit2	10.07	3.98	29.463	1512.67	29.30	37.70	3617.50	0.81	11.18
Average					29.95	37.35	3471.80	0.87	10.13
Tech Spec					**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Difference					-	-	-	-	-

Table A1.10 Tensile strength test results for aged test specimens.

Test piece	*Width (mm)*	*Thickness (mm)*	*Initial length (mm)*	*Peak load (N)*	*Tensile strength, yield (MPa)*	*Tensile strength, ultimate (MPa)*	*Tensile modulus (MPa)*	*Elongation at yield (%)*	*Elongation at break (%)*
ID1 A1h bit1	10.00	4.02	28.232	2119.32	27.90	52.70	2268.20	1.23	3.57
ID1 A1h bit2	9.99	4.03	27.373	2132.55	32.00	53.00	2172.70	1.47	3.70
ID1 A1h bit3	9.97	4.01	28.193	2133.84	42.80	53.40	2109.60	2.03	3.34
Average					34.23	53.03	2183.50	1.58	3.54
Tech Spec					**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Difference					-	-	-	-	-
ID1 A1hm bit1	9.98	4.03	29.024	1977.61	34.50	49.20	2003.90	1.72	3.42
ID1 A1hm bit2	10.00	4.02	28.759	1946.87	38.50	48.40	2100.70	1.83	2.55
ID1 A1hm bit3	10.01	4.04	27.563	1935.12	36.50	47.90	1829.70	2.00	3.16
Average					36.50	48.50	1978.10	1.85	3.04
Tech Spec					**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Difference					-	-	-	-	-
ID1 A2h bit1	9.96	4.26	28.447	1960.52	27.50	46.20	2044.80	1.35	4.18
ID1 A2h bit2	9.94	4.23	29.661	1978.80	30.60	47.10	1871.50	1.64	4.29
ID1 A2h bit3	9.95	4.26	27.848	1972.34	32.10	46.50	1864.10	1.72	4.50
Average					30.07	46.60	1926.80	1.57	4.32
Tech Spec					**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Difference					-	-	-	-	-
ID1 A3h bit1	10.09	4.16	28.019	1027.67	22.00	24.50	1547.20	1.42	1.63
ID1 A3h bit2	10.11	4.18	28.648	1231.73	14.80	29.10	1916.20	0.77	1.86
ID1 A3h bit3	10.08	4.16	28.068	1149.10	21.60	27.40	1602.90	1.35	1.84
Average					19.47	27.00	1688.77	1.18	1.78
Tech Spec					**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Difference					-	-	-	-	-
ID6 A1h bit1	10.28	4.02	28.140	1794.36	28.10	43.40	2995.30	0.94	3.42
ID6 A1h bit2	10.27	4.01	26.856	1784.12	27.60	43.30	2921.20	0.95	3.21
ID6 A1h bit3	10.33	4.05	26.561	1799.82	26.90	43.00	2940.80	0.91	3.51
Average					27.53	43.23	2952.43	0.93	3.38
Tech Spec					**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Difference					-	-	-	-	-

Table A1.11 Tensile strength test results for aged test specimens.

Test piece	*Width (mm)*	*Thickness (mm)*	*Initial length (mm)*	*Peak load (N)*	*Tensile strength, yield (MPa)*	*Tensile strength, ultimate (MPa)*	*Tensile modulus (MPa)*	*Elongation at yield (%)*	*Elongation at break (%)*
ID6 A3h bit1	10.03	4.06	29.639	1734.51	27.30	42.60	2534.00	1.08	4.13
ID6 A3h bit2	10.05	4.08	28.105	1721.98	25.80	42.00	3123.70	0.83	3.20
ID6 A3h bit3	10.03	4.01	28.808	1668.18	30.30	41.50	2853.60	1.06	2.34
Average					27.80	42.03	2837.10	0.99	3.22
Tech Spec					**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Difference					-	-	-	-	-
ID9 A1h bit1	10.05	4.22	27.208	1594.38	22.90	37.60	3028.90	0.76	1.78
ID9 A1h bit2	10.05	4.17	27.935	1543.53	23.10	36.80	2795.80	0.83	1.79
ID9 A1h bit3	10.02	3.95	27.827	1288.93	24.70	32.60	2657.00	0.93	1.74
Average					23.57	35.67	2827.23	0.84	1.77
Tech Spec					**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Difference					-	-	-	-	-
ID12 A1h bit1	10.18	4.33	28.568	1946.75	31.20	44.20	3555.00	0.88	7.86
ID12 A1h bit2	10.21	4.29	28.538	1933.62	32.40	44.10	4279.00	0.76	8.61
ID12 A1h bit3	10.21	4.33	28.302	1929.56	35.20	43.60	4019.20	0.88	8.62
Average					32.93	43.97	3951.07	0.84	8.36
Tech Spec					**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Difference					-	-	-	-	-
ID13 A1h bit1	9.88	4.11	27.179	981.32	24.20	24.20	3796.60	0.64	0.64
ID13 A1h bit2	9.91	4.02	28.847	1023.61	25.70	25.70	2666.20	0.96	0.96
ID13 A1h bit3	9.90	4.14	29.145	970.22	23.70	23.70	2613.30	0.91	0.91
Average					24.53	24.53	3025.37	0.84	0.84
Tech Spec					**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
Difference					-	-	-	-	-

Table A1.12 Izod impact strength test results.

Test specimen	*Width (mm)*	*Thickness (mm)*	*Absorbed energy (J)*	*Area (m²)*	*(J/m²)*	*(J/m)*
ID1 B bit1	12.66	5.37	0.232	5.46E-05	4252.26	43.20
ID1 B bit2	12.64	5.36	0.224	5.45E-05	4113.29	41.79
ID1 B bit3	12.67	5.35	0.240	5.44E-05	4415.34	44.86
ID1 B bit4	12.66	5.35	0.216	5.44E-05	3973.80	40.37
ID1 B bit5	12.66	5.36	0.200	5.45E-05	3672.58	37.31
Average ID1			0.222	5.44E-05	4085.45	41.51
Tech Spec					**N/A**	**135.00**
Difference					**-**	**-93.49**
ID2 B bit1	12.73	5.19	0.192	5.27E-05	3641.16	36.99
ID2 B bit2	12.72	5.16	0.120	5.24E-05	2288.96	23.26
ID2 B bit3	12.74	5.15	0.176	5.23E-05	3363.66	34.17
Average ID2			0.163	5.25E-05	3097.93	31.47
Tech Spec					**N/A**	**64**
Difference					**-**	**-32.53**
ID3 B bit1	12.70	5.12	0.320	5.20E-05	6151.57	62.50
ID3 B bit2	12.73	5.13	0.312	5.21E-05	5986.09	60.82
ID3 B bit3	12.74	5.11	0.336	5.19E-05	6471.79	65.75
Average ID3			0.323	5.20E-05	6203.15	63.02
Tech Spec					**N/A**	**128.00**
Difference					**-**	**-64.98**
ID4 B bit1	12.71	5.14	0.128	5.22E-05	2451.06	24.90
ID4 B bit2	12.77	5.15	0.160	5.23E-05	3057.87	31.07
ID4 B bit3	12.74	5.18	0.136	5.26E-05	2584.14	26.25
Average ID4			0.141	5.24E-05	2697.69	27.41
Tech Spec					**N/A**	**41.00**
Difference					**-**	**-13.59**
ID5 B bit1	12.76	5.07	0.104	5.15E-05	2018.98	20.51
ID5 B bit2	12.71	5.08	0.136	5.16E-05	2635.01	26.77
ID5 B bit3	12.69	5.07	0.128	5.15E-05	2484.90	25.25
Average ID5			0.123	5.15E-05	2379.63	24.18
Tech Spec					**4400.00**	**N/A**
Difference					**-2020.37**	**-**
ID6 B bit1	12.88	5.21	0.160	5.29E-05	3022.65	30.71
ID6 B bit2	12.80	5.23	0.192	5.31E-05	3613.32	36.71
ID6 B bit3	12.83	5.16	0.144	5.24E-05	2746.75	27.91
Average ID6			0.165	5.28E-05	3127.57	31.78
Tech Spec					**4400.00**	**N/A**
Difference					**-1272.43**	**-**
ID7 B bit1	12.75	5.21	0.144	5.29E-05	2720.39	27.64
ID7 B bit2	12.71	5.19	0.136	5.27E-05	2579.16	26.20
ID7 B bit3	12.72	5.19	0.144	5.27E-05	2730.87	27.75
Average ID7			0.141	5.28E-05	2676.81	27.20
Tech Spec					**4200.00**	**N/A**
Difference					**-1523.19**	**-**

Table A1.13 Izod impact strength test results.

Test specimen	*Width (mm)*	*Thickness (mm)*	*Absorbed energy (J)*	*Area (m²)*	*(J/m²)*	*(J/m)*
ID8 B bit1	12.64	5.04	0.328	5.12E-05	6405.45	65.08
ID8 B bit2	12.70	5.04	0.368	5.12E-05	7186.60	73.02
ID8 B bit3	12.65	5.00	0.296	5.08E-05	5826.77	59.20
Average ID8			0.331	5.11E-05	6472.94	65.77
Tech Spec					**N/A**	**N/A**
Difference					**-**	**-**
ID9 B bit1	12.61	5.07	0.104	5.15E-05	2018.98	20.51
ID9 B bit2	12.51	5.04	0.104	5.12E-05	2031.00	20.63
ID9 B bit3	12.63	4.87	0.104	4.95E-05	2101.89	21.36
Average ID9			0.104	5.07E-05	2050.62	20.83
Tech Spec					**N/A**	**32.00**
Difference					**-**	**-11.17**
ID10 B bit1	12.90	5.13	0.232	5.21E-05	4451.20	45.22
ID10 B bit2	12.83	5.11	0.216	5.19E-05	4160.44	42.27
ID10 B bit3	12.77	5.13	0.200	5.21E-05	3837.24	38.99
Average ID10			0.216	5.21E-05	4149.63	42.16
Tech Spec					**N/A**	**41.00**
Difference					**-**	**1.16**
ID11 B bit1	12.70	4.81	0.288	4.89E-05	5893.23	59.88
ID11 B bit2	12.70	4.84	0.304	4.92E-05	6182.08	62.81
ID11 B bit3	12.72	4.75	0.376	4.83E-05	7791.13	79.16
Average ID11			0.323	4.88E-05	6622.15	67.28
Tech Spec					**N/A**	**74.00**
Difference					**-**	**-6.72**
ID12 B bit1	13.00	5.34	0.136	5.43E-05	2506.71	25.47
ID12 B bit2	13.00	5.26	0.104	5.34E-05	1946.05	19.77
ID12 B bit3	12.97	5.30	0.104	5.38E-05	1931.36	19.62
Average ID12			0.115	5.38E-05	2128.04	21.62
Tech Spec					**N/A**	**N/A**
Difference					**-**	**-**
ID13 B bit1	12.74	5.04	0.048	5.12E-05	937.38	9.52
ID13 B bit2	12.77	5.04	0.048	5.12E-05	937.38	9.52
ID13 B bit3	12.73	5.03	0.048	5.11E-05	939.25	9.54
Average ID13			0.048	5.12E-05	938.00	9.53
Tech Spec					**N/A**	**N/A**
Difference					**-**	**-**
ID14 B bit1	12.83	4.97	0.140	5.05E-05	2772.54	28.17
ID14 B bit2	12.82	4.98	0.188	5.06E-05	3715.65	37.75
ID14 B bit3	12.82	4.98	0.228	5.06E-05	4506.21	45.78
Average ID14			0.185	5.06E-05	3664.80	37.23
Tech Spec					**N/A**	**25.00**
Difference					**-**	**12.234**
ID15 B bit1	12.83	4.99	0.300	5.07E-05	5917.35	60.12
ID15 B bit2	12.80	4.99	0.304	5.07E-05	5996.24	60.92
ID15 B bit3	12.80	4.99	0.284	5.07E-05	5601.75	56.91
Average ID15			0.296	5.07E-05	5838.45	59.32
Tech Spec					**N/A**	**32.50**
Difference					**-**	**26.819**

Table A1.14 Izod impact strength test results for aged test specimens.

Test specimen	*Width (mm)*	*Thickness (mm)*	*Absorbed energy (J)*	*Area (m^2)*	*(J/m^2)*	*(J/m)*
ID1 Bh bit1	12.63	5.35	0.260	6.76E-05	4783.28	48.60
ID1 Bh bit2	12.64	5.36	0.252	6.78E-05	4627.45	47.01
ID1 Bh bit3	12.60	5.32	0.300	6.70E-05	5550.29	56.39
ID1 Bh bit4	12.64	5.35	0.252	6.76E-05	4636.10	47.10
Average ID1			0.266	6.75E-05	4899.28	49.78
Tech Spec					**N/A**	**135.00**
Difference					**-**	**-85.22**
ID6 Bh bit1	12.83	5.15	0.188	6.61E-05	3593.00	36.50
ID6 Bh bit2	12.82	5.22	0.188	6.69E-05	3544.82	36.02
ID6 Bh bit3	12.87	5.20	0.196	6.69E-05	3709.87	37.69
Average ID6			0.191	6.66E-05	3615.90	36.74
Tech Spec					**4400.00**	**N/A**
Difference					**-784.10**	**-**
ID9 Bh bit1	12.49	5.04	0.136	6.29E-05	2655.92	26.98
ID9 Bh bit2	12.49	4.83	0.128	6.03E-05	2608.37	26.50
ID9 Bh bit3	12.55	4.96	0.136	6.22E-05	2698.76	27.42
Average ID9			0.133	6.18E-05	2654.35	26.97
Tech Spec					**N/A**	**32.00**
Difference					**-**	**-5.03**
ID12 Bh bit1	12.94	5.28	0.144	6.83E-05	2684.32	27.27
ID12 Bh bit2	12.99	5.34	0.080	6.94E-05	1474.53	14.98
ID12 Bh bit3	13.01	5.26	0.152	6.84E-05	2844.23	28.90
Average ID12			0.125	6.87E-05	2334.36	23.72
Tech Spec					**N/A**	**N/A**
Difference					**-**	**-**
ID13 Bh bit1	12.67	4.97	0.040	6.30E-05	792.15	8.05
ID13 Bh bit2	12.55	4.99	0.040	6.26E-05	788.98	8.02
ID13 Bh bit3	12.55	5.00	0.040	6.28E-05	787.40	8.00
Average ID13			0.040	6.28E-05	789.51	8.02
Tech Spec					**N/A**	**N/A**
Difference					**-**	**-**