CHALMERS
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Using Recycled and Bio-Based Plastics for Additive Manufacturing

A Case Study on a Low Volume Car Component

Master’s Thesis in Product Development

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Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

The Automotive industry is currently facing huge challenges to reduce the environmental impact from plastics used in cars. Meanwhile, additive manufacturing (AM) is gaining increased interest in the industry and researchers predict a continued increased implementation. Studies have shown that AM can provide several benefits when it comes to reducing environmental impact. Until recently, however, little focus has been put into developing new types of sustainable plastics to be used in AM-machines.

In this thesis, 53 different types of recycled plastic and bioplastic filaments for fused deposition modelling (FDM) machines are evaluated from a case study perspective on a car interior component. Seven of the most suitable materials are tested with regards to mechanical and thermal properties in a lab environment. From the tests it is evident that recycled plastic filament can perform equally well as virgin plastics although with slightly larger variation in material properties. Among the materials tested, a recycled ABS material called Re:Add ABS showed overall best performance. Properties of bio-based alternatives still appears to be too poor to be realistically implementable for printed car components.

When assessing the sustainability aspects of choosing recycled and bio-based plastics it is clear that recycled plastic is the best alternative from an environmental perspective. The larger weight of the bio-based material tested here resulted in a larger car fuel consumption which cancelled out the lower impact during material production. Also, from a cost perspective, the Re:Add ABS was comparable to the virgin ABS alternative.

In conclusion, a significant reduction in environmental impact can be achieved by choosing recycled ABS materials. When it comes to mechanical and thermal properties the recycled material has been showed to be almost as good as virgin alternatives which leads to several possibilities of implementing these types of material in automotive industry.

Keywords: Sustainability, Additive Manufacturing, Fused Deposition Modelling, Recycled plastic, Low Volume, Bioplastic, Automotive, Volvo Cars

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Contents

Abbreviations

Abbreviation	Meaning
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
ASTM	American Society for Testing and Materials
CAD	Computer Aided Design
CDS	Centre Display Screen
CES	Cambridge Engineering Selector
CO_2	Carbon Dioxide
DSC	Differential Scanning Calorimetry
DED	Direct Energy Deposition
EU	European Union
FDM	Fused Deposition Modelling
HDT	Heat Deflection Temperature
HIPS	High Impact Polystyrene
HDPE	High Density Polyethylene
HT-PLA	High Temperature Polyactic Acid
HVAC	Heating, Ventilating, and Air Conditioning
IP	Instrument Panel
LCA	Life Cycle Assessment
LFT	Long Fibre Thermoplastic
NO_x	Nitrogen Oxides
OEM	Original Equipment Manufacturer
OECD	Organisation for Economic Co-operation and Development
PA	Polyamide
PC	Polycarbonate
PE	Polyethylene
PET	Polyethylene Terephthalate
PLA	Polylactic Acid
PSS	Product Service System
PUR	Polyurethane
PVA	Polyvinyl Alcohol
rPET	Recycled Polyethylene Terephthalate
SO_x	Sulphur Oxides
TPU	Thermoplastic Polyurethane
UN	The United Nations
UV	Ultra Violet
VCS	Volvo Cars Standard


KSZ 878

1 Introduction

This chapter introduces the background and goal formulation with the corresponding research questions for this thesis. A general background first describes the wide context of sustainability, additive manufacturing, and the automotive industry before connections between the areas are presented. The purpose and aim for this work are then defined and an overview of this report is presented.

1.1 Background

The automotive industry face a tremendous challenge to decrease the environmental impact of the sector. Governments, organisations and customers expect constant progress and directives are set to ensure it. The emission related to the usage phase of vehicles has been in the public focus for some time. However, to determine the total environmental impact of vehicles the whole life cycle must be taken into consideration, covering all phases from raw-materials extraction to end of life treatment.

Material erosion, growing landfills and pollution of land as well as ocean are global issues in great need to be addressed. One of the materials contributing to these problems is plastic. The global fossil-based plastic consumption has reached untenable volumes, while the number of plastic components in cars has constantly been scaled up. In order to improve the environmental impact throughout the life-cycle of vehicles the choice of material is essential and Volvo Cars is currently investigating the possibilities of using recycled plastic, bioplastic and bio composites. Sustainability commitment is one of Volvo Cars key elements in their corporate strategy, and environment is one of three core values within the company. All the above points to the importance of being fully dedicated to sustainable development at Volvo Cars.

To further accelerate the sustainability effort, alternative manufacturing processes are considered. Additive manufacturing is a growing trend within the automotive industry and is expected to continue grow in the upcoming years. Except enabling new types of structures, AM has shown to be a process with great potential from a sustainability perspective. The design freedom coming with additive manufacturing makes design optimization less restricted than before, leading to possibilities to reduce material usage and product weight. Other advantages, as reduced need of component shipping and warehousing, can also be achievable with AM.

One of many AM technologies is Fused Deposition Modelling (FDM), which is a well-established technology already used within the automotive industry for prototyping, manufacturing of tools and low volume production. Even though FDM is a relatively mature technology, new types of sustainable materials for FDM-machines have just recently entered the market. Due to the novelty of these sustainable plastic materials there are many questions still to be answered. Research in the area is limited, and there are no known applications within the automotive industry for these sustainable FDM materials. An opportunity to investigate the possibilities of sustainable plastics for FDM has therefore been identified.

1.2 Purpose and Problem Definition

The aim of this thesis is to investigate the possibilities and limitations of using recycled plastics and bioplastics for additive manufacturing. By investigating the market, internal development work at Volvo Cars, competitors, and related industries the current state of the technology is mapped and evaluated. Promising materials are identified, tested and applied to a component in a case study. An analysis of the environmental impact of the component is conducted before a prototype is created. A cost calculation is performed and followed by an evaluation of the concepts plausibility and possibilities for further development. Finally, a recommendation is presented suggesting how to proceed with the findings and how to how Volvo Cars can work with these technologies.

1.2.1 Goal Formulation

The goal is to investigate the potential and limitations of printing a car component with sustainable plastic filament and present an assessment including cost calculation and an environmental impact evaluation.

1.3 Research Questions

- What is realistic to achieve with FDM-technology in sustainable plastics?
- How does material properties of sustainable plastic compare to virgin plastics when used in FDM-machines?
- Is it possible to improve profitability and decrease environmental impact by combining AM and sustainable plastics at Volvo Cars?

1.4 Delimitations

The project is conducted at the department of Strategy and Innovation, which is a subgroup of Vehicle Hardware. Therefore, components belonging to other departments are excluded, for example propulsion components and electronics.

Other materials than plastics are excluded in order to limit the scope of the work. More specific: recycled plastics, bioplastics and bio composites are included. These types of materials are already under investigation at Volvo Cars and in automotive industry in general. This limitation thereby puts this thesis in a context relevant in automotive industry today.

The component used for the case study is not exposed to heavy loads nor a part of the crash-safety structure. Verifying the properties of a new material or manufacturing process for such a component would be too time consuming considering the time frame for this thesis.

For printing, FDM-printers are used. The combination of additive manufacturing and sustainable polymers is fairly new and the access to these types of materials is therefore limited. FDM-technology is used both in consumer and industrial printers which makes testing and acquiring of material easier. FDM is also the technology for which most types of new sustainable materials are being developed.

1.5 Report Outline

This report is organized to show the working process and the chapters are organized as a timeline, meaning that methods and results are presented for each chapter individually. The purpose of this is to allow the reader to better follow the decision processes. In Figure 1.1, the report outline is summarised.

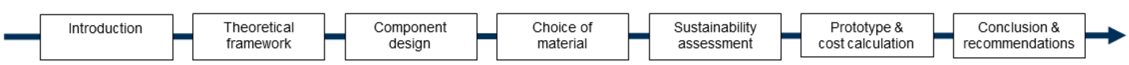

Figure 1.1: Overview of the report outline.

In Chapter 2, the theoretical framework is laid out. This involves literature studies regarding sustainability in general, sustainable plastics and additive manufacturing. Chapter 3 described the process of choosing a car component suitable for the case study. Chapter 4 includes all work related to material evaluation. It starts with a market assessment and screening among available materials. This is followed by extensive testing of seven of these materials in a lab environment. In Chapter 5 three materials are assessed from a sustainability perspective, where one of them is the selected material for the case study. The process of manufacturing and testing the prototype in the chosen material is then presented in Chapter 6, together with a cost calculation for the component. All results and knowledge generated are put together in Chapter 7 to answer the three research questions stated in the beginning. This also includes recommendations to Volvo Cars regarding how additive manufacturing with sustainable plastics can realistically be implemented.

2 Theoretical Framework

In this chapter, the current state of sustainable plastics and additive manufacturing is presented. It includes an overall view on sustainability and how it relates to Volvo Cars. Also, a description and definition of the terms often used when discussing sustainable plastics are presented. A similar overview is included for additive manufacturing in general and then for fused deposition modelling specifically.

2.1 Sustainability

Sustainable development can be described as “technology development which makes it possible to improve the current state to a more sustainable one” [1]. The concept of sustainability is present in a wide range of settings and the global awareness of sustainability has never been higher. However, it was not long ago the sustainability terminology, as we know it today, was defined. In “Our Common Future” published by the United Nations in 1987 [2] the term was defined as followed:

> *“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs”*

Sustainability is an interplay between environmental, economic and social factors, further presented in the United Nations 17 sustainability goals, from 2015 [3]. Four of the goals strongly connected to this project are: (9) industry, innovation and infrastructure; (11) sustainable cities and communities; (12) responsible consumption; and (13) climate action. Sustainable development is discussed in a wide range of settings with various applications. This variation, in combination with being globally used, has led to different interpretations of the terminology and what to be associated with it [1]. It has been shown that geographical area affect what people associate with sustainability, where sustainable development in some parts of the world is not necessary considered sustainable in other parts.

However, one global sustainability issue hard to deny is the overconsumption of raw materials. The world’s resources are extracted in an unsustainable speed and some materials have already reached their ecological limits. In 40 years the raw material extraction has gone from 22 billion tons in 1970 to 70 billion tons in 2010 [4]. Moreover, the use of raw material is not expected to be less of a problem in the future as the demand is constantly increasing due to economic and population growth. Economic growth leads to an enhanced life standard which has a direct relation to increased consumption, In fact, economic growth has proven to have a larger impact on the raw material usage than population growth [4].

Economic or population growth are not aspects the industry can do much about, however, resource utilization is. In 2015 the raw material extraction alone stood for more than 20 % of the total CO_2 emission in Sweden [5]. The resource shortage can only be solved if the natural resources are utilized more efficiently and within the ecological limits. Recycling is one way to make use of materials already in circulation, which also lead to a decoupling between economic growth and natural resource use. Sweden and other countries with well-developed infrastructure are well equipped to take the lead and set an example for the rest of the world in this area. It starts from within, to take responsibility for what we produce and for what happen with the used material resources after the products lifetime.

According to Janez Potočnik, member of the International Resource Panel, the industrial efforts has for a long period of time been focused on product performance and reduction of energy consumption, while less effort has been put in development of more sustainable materials [6]. Therefore, he encourages industries to take a stand in the fight for sustainable materials. In his opinion, there will not be economic incitements to halt this unsustainable material use before the environmental and health consequences, already present in some contexts, will be very much real.

"In the mid-term, except in specific cases, resource shortage will not be limiting our economic development, the environmental and health consequences caused by this excessive and irresponsible use of resources will be" (Janez Potočnik)

2.1.1 Circular Economy

Circular economy is a model where the economic growth is decoupled from the natural resource use. By seeing products as raw material banks instead of waste products the whole anticipation of the product life cycle and the system around it can be evolved. This is illustrated in Figure 2.1 where the circular economy butterfly model is shown, with different levels of resource efficient ways to reuse material. By circulating materials the need for raw material decreases as the value of the material is restored for an extended amount of time. The inner circle is the best option, if possible, while the outer is the last alternative.

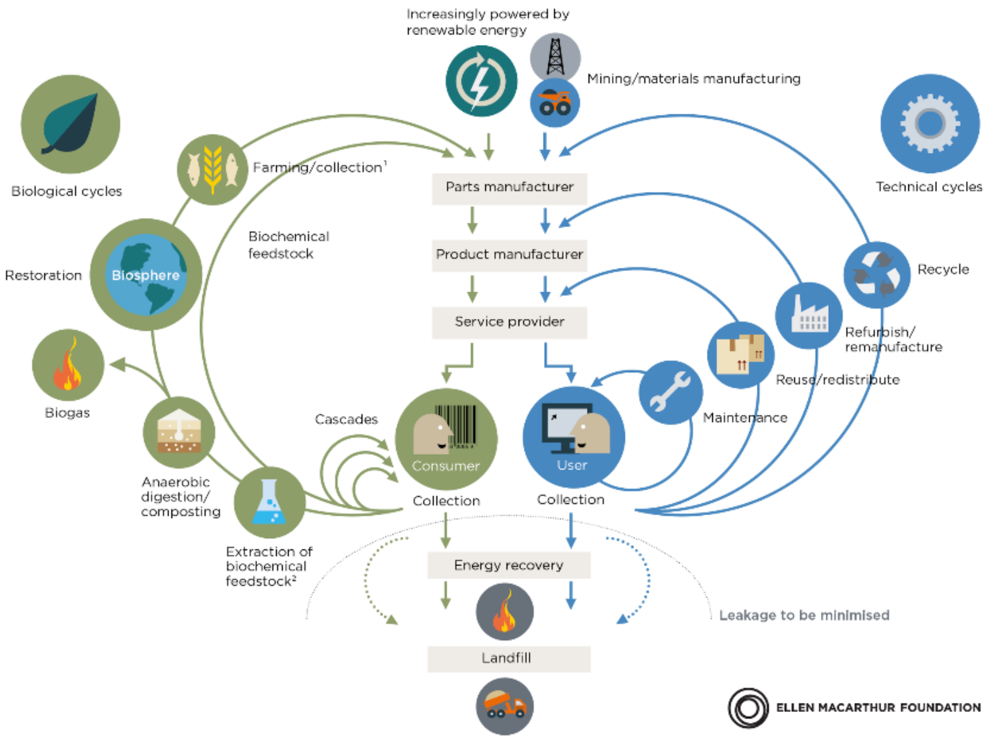

Figure 2.1: The Circular Economy model from Ellen Macarthur Foundation adapted from the book Cradle to Cradle by William McDonough and Michael Braungart [7].

The advantages of implementing a circular economy are many. By following the model the sustainability of a product is maximized and the materials are utilized in the most efficient way. Furthermore, the model is a way to extend the life of products, and in turn create an opportunity to generate more income over a products life cycle. As product service systems (PSS) become more common in the automotive industry the incentives to work for a more circular economy will inevitably increase.

Even though the potential and possibilities of circular economy is well understood and often recognised, the scientific base on which the theory is built is rather small. Research has pointed out the fact that the circular economy concept has been developed mainly by the policy-makers and the business community [8]. The authors claims that the attempts to define and describe circular economy from a scientific perspective, and attempts to assess the actual sustainability impacts, has been limited. In the research [8] some important limitations of the concept are described. One of the limitations pointed out is the assumption that a longer life-time through reuse and refurbishment always lead to net improvements from a sustainability point of view. As pointed out, this might not be true in all cases considering that a shorter life-time can result in faster implementation of new technology and innovations improving the sustainability of the product. What is optimal for each case must be assessed individually by taking all sustainability aspect into consideration, something that typically is hard and complex if even possible. The same researchers also describes the thermodynamic laws of physics as one important aspect to remember. In their view, the inevitable loss of material/product performance over time will always lead to emissions and waste. A large global economic growth might therefore still offset the gains made by introducing circular economy. If so, even more drastic changes are needed to establish a sustainable global society

2.1.2 Sustainability at Volvo Cars

Sustainable development within automotive industry has many different faces due to the size of the companies. Ashby presented 15 areas involving sustainability work important to consider within the sector, see Table 2.1. All categories are interlinked in some way, making it difficult to work with one area without entering another.

Table 2.1: Sustainability areas within automotive industry [9].

Energy	Emissions	Exploitation
Materials	Environment	Efficiency
Space	Policy	Safety
Resources	Politics	Human patience
Economies	Legality	Social acceptance

One of the areas mentioned by Ashby is environment which also is one of Volvo Cars' three core values, together with quality and traffic safety. The Volvo brand is deeply entrenched with safety and quality, however, environment has not established as strong recognition. The Swedish nature is seen to be a repetitive element in the marketing strategy, visualizing the Swedish ideal by mixing countryside, forest and marine environments. The chosen marketing approach facilitate for Volvo to build an environmental friendly brand reputation, where sustainable development progresses may be implemented to reinforce the image further.

Sustainability commitment is one out of five strategic focus areas, making sustainable development a part of the company strategy. Volvo Cars has implemented a sustainability programme to initiate sustainability commitment throughout the organisation and to guide the strategic decision making. The program is called "Omtanke" and concerns 12 of the 17 UN sustainable development goals. The program aims at achieving sustainable profitability and growth by pursuing a clean, safe and responsible business [10]. Another example of sustainability actions is described in Volvo Cars Sustainability Report 2016, where the long term target to increase the quantities of renewable materials and recycled non-metallic materials is presented [10].

"We take pride in our role within society and are focused on reducing our environmental impact" (Volvo Cars)

The efforts to create a more sustainable business are going beyond the Volvo Cars brand itself. As owner of one of the world's toughest sailing events, where the participants sail around the world, Volvo Cars has taken a stand against the ocean pollution. In the Ocean Race summit 2015 a document was published describing the large amount of ocean waste witnessed by sailors during the race. Since then the race has been used as a platform to put focus on ocean health. An extensive sustainability programme for the 2017-2018 race has been launched, with three key pillars:

minimising the environmental footprint of the race, maximise impact by using the global platform to spread awareness, and contribute by collecting data at sea to science [11]. The goal with the ocean health initiative is to be involved and make a lasting impact by working to “Turn the Tide on Plastic”.

2.2 Sustainable Plastics

Plastic is one of the most used material worldwide with an annual production of 322 megatons in 2016 [12]. The vast majority of the plastic produced is made from fossil hydrocarbons, particularly oil. This is an ever increasing problem for a number of reasons [9]:

- oil is a non-renewable resource;
- the carbon contained in a fossil-based plastics will eventually be released into the atmosphere when used;
- companies being dependent on oil exposes themselves to a risk of cost volatility and supply variations, and
- most fossil hydrocarbons degrade very slowly leading to problems with plastic pollution in the nature, especially the oceans.

Due to these risk, there has been an increasing effort towards a more sustainable use of plastic materials, also in automotive industry. The automotive industry is the third largest consumer of plastic in Europe, with 8.9 % of the total yearly demand in 2015 [12]. Today polymers from end of life cars in Sweden are fragmented and either incinerated or deposited [5]. There are a number of ways in which different levels of increased sustainability can be achieved in plastic components, where recycled plastic, bioplastic and bio composites are three alternatives. In the following sections, these terms are introduced and defined.

2.2.1 Recycled Plastic

After the usage phase of a plastic product there are four general waste treatments possibilities: reuse, material recovery, energy recovery and landfilling [12]. Material recovery, often called recycling, can be divided into mechanical recycling and chemical/feedstock recycling. Analyses of the life-cycle of some of the most common plastic materials have shown that mechanical recycling generally is the most sustainable waste-treatment alternative [13]. Although chemical recycling is under rapid development and provides some important benefits compared to mechanical recycling.

Mechanical recycling processes are individual for different materials and how well the material is recovered to its initial state differ. Plastics are one of the more challenging materials to recycle and the reasons are manifold; many different mixtures, reinforcements, wide range of colours, substantial quality loss and large energy demands are some of them. Plastics collected at recycle facilities are sorted, cleaned and dried before the quality is examined. To ensure the plastic is stable and miscible, additives are added before the material is ready to be processed again. The final outcome is affected by the mixture of plastics, what additives that have been used and the ageing of the material [14]. In 2016, about 8.4 megatons of plastic were collected for recycling globally [15]. The amount of plastic recycled within EU has increased by 79 % between 2006 and 2016. 2016 was also the year when, for the first time, the amount of recycled plastic in EU was greater than the landfilled amount. However, EU still exports 50 % of all plastic waste outside their borders [5].

In chemical recycling, chemical processes are used to convert polymers into the original monomers. This technology has the benefit of being less dependent on sorting the plastics before processing. Even though most polymers are possible to recycle chemically the energy required for the process is still too large to make it profitable for most polymers. One exception is PET plastics, where the method is used in large scale. Due to the large energy consumption, these so called pyrolysis facilities need to be rather large to be profitable which is why all recycled PET from Sweden is processed in the Netherlands [14].

2.2.2 Bioplastic

Bioplastics is a fast growing group of plastics, although from a low level. The yearly production was 2.0 megatons in 2017 which represent less than 1 % of the total global plastic production. Production is, however, forecasted to increase to 9.2 megatons by 2021 [16].

Bioplastics are generally defined as polymer materials that are made from renewable raw materials and/or are biologically degradable [17]. Bioplastics can be divided into three categories: biodegradable petrochemical-based, biodegradable bio-based and non-biodegradable bio-based. Figure 2.2 shows the fundamental differentiation between bioplastics and conventional plastics.

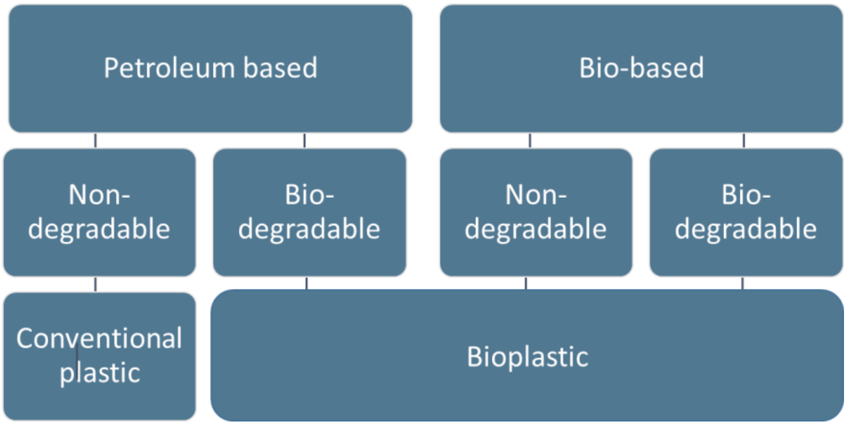

Figure 2.2: A model showing what goes under the term bioplastics.

Bio-based plastics are typically made from corn or sugar cane crops. Among the bio-based plastic, 37 % of the produced amount is biodegradable and 63 % is non-biodegradable [16]. Biodegradable materials can be disintegrated by bacteria, fungi or other purely biological means. This significantly reduces the problem of plastic pollution in natural environments. While non-biodegradable bioplastics suffers from similar pollution problems as regular plastics.

The most commonly used bioplastics are the so-called “drop-ins” which are bio-based versions of the regular bulk plastics, such as PE and PET. Bio-PET is the by far most used bioplastic with 41.5 % of the total bioplastic production. It is followed by biodegradable polyester with 11.7 % and bio-PLA with 10.6 % [16]. Since the drop-ins have an identical chemical structure as their petrochemical equivalent, they also have the same mechanical properties. In 2017, the price was however still 20-30 % higher compared to bulk plastics [17].

In addition to the material recovery alternatives described above, bioplastics provide some additional alternatives. Bioplastics can be used to produce biogas through fermentation which can be used as an energy source. Biodegradable bioplastics can also be decomposed trough composting. Mechanical recycling is, however, still the preferred treatment also for bioplastics from an environmental perspective [18].

2.2.3 Bio-Composite

A bio-composite material consists of a matrix component and reinforcement component, where at least one of the components is bio-based. Among the more well-known materials in this category are the natural fibre reinforced plastics [17]. In these materials, regular plastics or bioplastics are used as matrix material and different types of natural fibres, such as wood fibres, are mixed in as reinforcement. This improves the mechanical properties of the material similarly as when glass or carbon fibre reinforcements are used.

The total yearly production of composite materials in Europe was 2.4 megatons in 2012 [19]. Bio-composites constitute about 15 % of this production. After the construction sector, automotive industry is the largest user of bio-composite materials. German car manufacturers are leading the use of these types of materials while Swedish manufacturers are still far behind [19]. The use of long fibre reinforced thermoplastic (LFT) is one of the most rapidly increasing material categories in this field. Bio-based LFT is more expensive than competing materials but higher quality and lower weight can offset the price difference [19].

2.2.4 Current State within the Automotive Industry

The use of more sustainable plastic materials is a concern for all car manufacturers today. Most competitors to Volvo Cars put in large amount of resources into developing solutions to enable implementation of more bio-based and recycled materials in their cars. In this section, some examples of successful applications of these types of materials are described.

One of Toyota's six sustainability challenges is contributing to a recycling-based society. As a part of this effort, they have developed a bio-based PLA plastic for automotive applications, which they claim to be first with [20]. In their SAI model, launched in August 2013, they covered 80 % of the interior surface area with bio-based plastics. Bioplastic materials are used for several applications such as door trim ornaments, seat cushioning, ceiling covering, trunk door trim, floor carpets etc. Toyota also have a system for collection and recycling of bumpers as well as a program for designing components to be easily disassembled as a way of making cars more recyclable [21].

Nissan is also developing methods for recycling of car bumpers. Damaged bumpers are collected all over Japan and then pulverized. The material is then recycled into bumpers for both new cars and as spare part bumpers [22]. Nissan is also using recycled plastic from PET bottles to produce dashboard sound insulation layers. They also use material from recycled plastic bottle caps in their automobile parts.

At Ford, they have used recycled plastics to develop fabrics made out of at least 25 % recycled material [23]. They are currently using these type of fabrics in twelve models. Also, they have implemented several new types of bio-based material in their cars. According to Ford, these types of material can be lighter and meet all durability and performance requirements. In the F-150 model, bio-based materials are being used for sound insulation, seat cushioning, wiring harness and underbody cover, just to mention a few applications. Another implemented bio-based material group is bio-composites [23]. Cellulose fibres have replaced fibreglass in their centre console armrests. Wheat-straw fibres are used in plastic storage bins and kenaf fibres are used in compression-moulded plastic door parts. Research is also being conducted into using even more types of natural fibres such as bamboo and agave.

Bio-materials in the car interior is also seen in BMW's cars. BMW I3 has interior trims in eucalyptus and other interior parts in plastic reinforced with 30 % kenaf fibre and olive-leafs have been used to colour leather details [24]. Volkswagen has, similar to BMW, interior parts in both bio-materials and recycled materials. Some examples are interior trim parts in natural fibre reinforced composites, for example door seats, doors, panels, seat backs, rear flap lining and parcel trays [25]. One of the plastics used is PE reinforced with hemp and flax. The load compartment floor has been made out of the less common material for automotive applications, recycled paper [26].

2.2.5 Laws & Regulations

In the US, EU, Japan, Korea and China, end of life vehicles must be 95 wt. % recyclable, reused or recovered [27]. Since it is a weight percentage regulation, denser materials have higher impact than light materials such as plastics. Plastics constitute 10-15 % of the total weight of a modern car, while it is closer to 50 % volume wise [28]. Moreover, the regulation allows for all recovered parts to be counted towards the 95 % which includes, for example, incineration of material. Currently there is no regulation pinpointing the issue of recycling plastic or the use of recycled plastic in new cars. However, new global directions are expected due to the excessed use of resources and the plastic pollution worldwide. One step in that direction is the European Union’s circular economy action plan for 2018, with the slogan “it is time to close the loop” [29]. The directive is a direct action to prevent the plastic polluting of land and oceans. One of the goals from the action plan is that single-use plastics should be made out of 100 % recyclable plastic by the year 2030.

2.3 Additive Manufacturing

Additive manufacturing is a fast growing manufacturing process that is attracting increasing interest from several industries. The first AM technologies were developed in the 1980s and have traditionally been used for rapid prototyping and tooling. The increased performance and optimization of the technology has however allowed for expanded use of AM in final production. In industries with complex high performance metal components, such as aerospace and medical industries, the technology is well established within final production. When it comes to automotive industry, the technology is still struggling with gaining economical advantage over traditional manufacturing methods. However, for low scale production it has been found to have a competitive advantage. In the following sections additive manufacturing is discussed first from a sustainability perspective before the automotive applications are presented.

2.3.1 Sustainability in Additive Manufacturing

Additive manufacturing provide several possibilities of increasing the sustainability of the design, manufacturing, use and recycling of products. Researchers have suggested that the increased use of AM in production can lead to an energy saving of up to 5 % in the manufacturing industry globally by 2025 [30]. They also point out automotive industry specifically as one of the industries with highest potential for AM adaption, although the problem of cost-efficient production in high volumes remains to be solved.

Several environmental benefits of AM in production have been shown. These include reduced waste compared to traditional processes due to the additive nature of the AM technology. Another important advantage is the possibility of optimizing the product design. AM allows almost unlimited design freedom which opens the door for increased use of topology optimized, and in other ways more resource efficient, components. Researchers have also pointed out the possibilities of more efficient supply chains as a result of increased use of additive manufacturing. Manufacturing sites can be less centralised since a large variate of geometries and materials can be produced in a single machine. Locally produced spare parts is one of the most discussed topics related to this.

Even though the potential of AM is well described, the degree to which the potential advantages are being realised is not well understood. Several researchers have investigated the energy consumption of AM processes in comparison to traditional processes such as injection moulding [31]. These studies, however, provide an inconclusive view on whether or not AM actually lowers the environmental impact. Several parameters need to be considered when investigating this issue. Drawing any general conclusion on lowered energy consumption by implementing AM is therefore not possible at the moment [32].

Even if the sustainability possibilities of additive manufacturing on a large scale is understood and well described in the literature, the issue of sustainable AM materials are not. When it comes to Fused Deposition Modelling, which is the technology investigated in this study, none of the large material manufacturers provide recycled materials. Also, the bio-based plastics available for industrial use are highly limited. In the past 3 to 5 years, several smaller firms and start-ups have, however, started to supply different types of more sustainable FDM materials. There are ways to circumvent the issue of not being able to use these new materials in industrial printers by using an available technology enabling usage of any filament in the industrial printers. However, these new materials are not specifically adapted for industrial printers and the same quality can therefore not be expected.

The AM market is expected to grow with an annual rate of 26 % till 2020 [33]. Thus, just as for traditional manufacturing methods, the sustainability of the material choice need to be addressed. One of the main issues related to this is the degradation of plastic materials for each time it is recycled. Studies have shown that recycling of PLA filament show the same trend of slightly reduced mechanical performance for each recycling as most other plastics [34]. The researches also stress that further investigation into the degradation of FDM filament is needed. Literature studies in the area of FDM materials have also pointed out the need for further evaluation of the mechanical properties of the types of sustainable materials described in this section [35].

2.3.2 Current State of Additive Manufacturing in Automotive Industry

As described earlier, car manufacturers are still struggling with making AM-technologies economically justifiable compared to traditional manufacturing methods. Many of the large automotive companies, as well as several smaller firms, are however evaluating the possibilities of the technology.

One example is Audi, who is using AM to produce spare parts. By having several printers around the globe they can produce spare parts to order and significantly reduce the need for storage and shipping of components [36]. Honda is using AM to provide several bespoke components to their customers [37]. This also allows for cost efficient manufacturing of limited edition components. Similar work is being done at Volkswagen who is using AM to produce special and exclusive series vehicles. They claim that the currently can profitably produce up to 200 units with AM. They also expect the technology to be cost efficient for up to 3000 units as a result of ongoing optimization efforts [38]. Ai Design is using FDM-machines to produce tailored interior components for high-end cars. By using several post-processing steps they can achieve surface finishes just as good as those from the OEMs [36].

When it comes to sustainable plastic materials within AM, not much have been done by the car manufacturers. Recycled plastics and bioplastics are hot topics within the industry, but with focus on traditional manufacturing methods. The development of sustainable materials for AM is still very much on a research level and the number of materials available on the market is highly limited. Within EU, a joint research project called BARBARA is currently developing new FDM compatible bioplastics to be used in car interior components [39]. Their goal is to produce materials that can compete with the mechanical properties of regular plastics and be printed in FDM machines.

2.3.3 FDM Technology

A number of different additive manufacturing processes exist and each technology provides different characteristics and allows different material families to be used. FDM is used to manufacture both high quality end products and simpler prototypes. The FDM-machines available on the market vary from open-source designs you build on your own to high performance production machines for industry applications, see Figure 2.3. The basic principle is, however, the same in all machines. A string of filament is fed through a heated nozzle which melts the material. By moving the nozzle horizontally over the printer bed, the material is deposited. When one layer has been added, the printer bed is lowered slightly and a new material layer is added. This process is repeated until the whole detail is built.

During the process it is important to ensure each new layer stick to the previous one as well as maintaining a smooth flow through the extrusion nozzle. Material properties such as low melting point and low viscosity are therefore essential to enable processing [40].

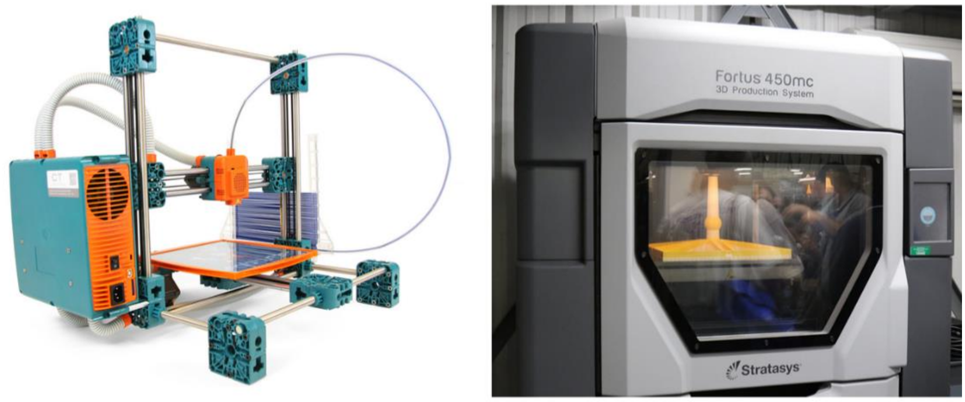

Figure 2.3: Examples of FDM-machines from consumer market (left) and industrial market (right).

Another aspect important to consider when working with FDM is the anisotropic mechanical behaviour of the printed parts [41]. Since the material is added as a melted plastic string layer by layer, the adhesion will be stronger in some directions and weaker in other, see Figure 2.4. This becomes extra critical to consider when doing material tests. Specimens printed with different material orientation need to be tested in order to fully evaluate and understand the material properties.

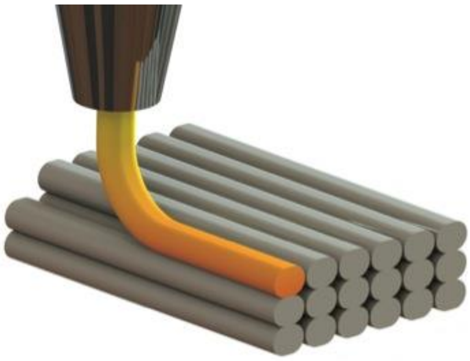

Figure 2.4: Principle illustration of the extrusion of FDM filament.

FDM-machines use filaments, where plastics materials are most common. A wide range of market offerings are available: pure plastics, material combinations, recycled plastics and fibre reinforced plastics. In Table 2.2 a number of the most commonly used FDM materials are presented. One of the materials is ABS. The material is easy to extrude and has good mechanical properties which, along with low cost, makes it one of the most widely used filaments for FDM. Another common material is PLA, normally made out for sugar or starch from renewable sources such as sugar cane, corn and potato [35]. Food packaging and disposal table wear are two applications for PLA, since the mechanical properties are typically insufficient for more demanding products.

PET materials are available both as virgin material and as recycled. The material is easy to print and is both hard, flexible, and odour free. HIPS is a material often used as support material, with similar properties as ABS. A wear-resistance material suited for machine parts is polyamide (PA), which is a lightweight material that can be re-melted and re-used without losing bounding properties. Other plastic materials worth mentioning, even though not covered further here, are polycarbonate (PC), high density polyethylene (HPDE) and flexible thermoplastic polyurethane (TPU) [35].

Table 2.2: Most commonly used plastic filaments for FDM.

Materials	Produced from	Properties	Pros	Cons
ABS	Petroleum	Durable, strong	Lightweight, slightly flexible, cheap	Create fumes, petroleum based, poor UV-resistance
PLA	Sugar cane, starch, etc.	Tough, strong	Bioplastic, non-toxic, low wrap, no odour	Fragile (brittle), low heat resistance
PVA	Petroleum	Water soluble, good barrier	Non-toxic, biodegradable, recyclable	Water absorbent, hard to store, expensive
PET	Petroleum	Strong, flexible, shock proof	No odours, recyclable	Absorbs moisture, FDA approved
HIPS	Petroleum	High impact resistance, soluble in limonene	Biodegradable, cheap	Warping
PHA	Sugars with biosynthesis	Stiff, brittle	UV-stable, stiffness	Elasticity, brittle
PA	Synthetic fibres	Strong, flexible, durable	Lightweight, water resistance, re-meltable	Emit toxic fumes

There are mainly three types of sustainable FDM filament materials available. The first one is filament made from recycled plastic. This is offered by a number of companies where the most common plastics are PET, ABS and PLA. The second material category is bioplastics. The most common materials in this category are PLA, PHA, PET and PVA. The third type of material is the bio-composites. These materials consist of regular, recycled or bio-based matrix material that is reinforced with natural fibres. The fibre portion in the material varies from a few percent up to 40 % [35]. Several types of wood such as bamboo, birch, cedar, cherry, pine, willow, cork and coconut are available as fibre material [42]. Also recycled carbon fibres are available as fillers in plastic filaments.





3 Choice of Component

To test the potential of a new type of plastic, and allow for concrete cost and environmental affect comparisons, a case study has been conducted on a car component. First, the car environment was studied to map areas with suitable plastic components. A few promising component categories could be identified, based on requirements received from several departments at Volvo Cars. By continually evaluating and excluding components a few promising case study alternatives were identified. The full process is described in this chapter.

3.1 Component Screening

To fully utilize the potential and benefits of additive manufacturing there a several aspects to consider. To make a cost efficient business case one must, first of all, consider the production volume. As described earlier, AM-technologies cannot compete cost wise with most traditional manufacturing methods on a large volume series production. Another factor, too often forgotten, is the need to design for AM. Components existing in cars today will be very ineffective to manufacture with AM since they are designed for completely different manufacturing processes. To enable utilization of the full AM potential, the increased design freedom it provides need to be taken to advantage.

To find components suitable for showing the potential of FDM in new types of plastic, a list of component requirements were generated. This was done in close collaboration with representatives from several departments at Volvo Cars. The most important requirements were that it should be a plastic component, not be part of crash-safety structure and not have a too demanding loading case. The full list of requirements is included in Table 3.1.

Table 3.1: List of requirements on components for case-study.

Criteria (demands)	**Justification**
Plastic component	Too time consuming to change material
Not part of crash-safety structure (chassis, steering wheel, seat structure etc.)	Would be too complex to verify and evaluate
Approximate static loading case	To enable strength evaluation

Criteria (desires)	**Justification**
Component with potential for design optimization	Ability to show increased potential from AM
Component with potential for customization	Ability to show increased potential from AM
Maximum 265x229x195 mm	In-house FDM-machine limitation
Low surface finish requirement	Reduces need for post-processing
Low design complexity	Limit design optimization work
Limited load on component	Less demands on material properties
Limited temperature exposure	Mechanical limitations on plastic material
Low exposure to moisture	Mechanical limitations on plastic material
Low exposure to UV-light	Mechanical limitations on plastic material
Low odour sensitivity	More material possible to use
Low production volume	Allows for a better business case

Based on these requirements, a number of potential components were identified. The selected components fulfil the demands stated in the requirement specification, although provide different level of fulfilment of the desires. The full list of potential components is summarised in Table 3.2.

Table 3.2: List of potential component for case study.

Component	**Part of car**
Interior door handle panel	Interior panels
Shift stick knob	Centre console
Dashboard air duct vent	Instrument panel
Centre air duct vent	Centre console
CDS Bracket (Centre Display Screen)	Instrument panel
Door centre bracket	Door structure
Bracket gear shift components	Centre console
Door bracket panel-locking mechanism	Door structure
ECM box (Engine Control Module)	Engine compartment
Air duct connection adapter	Instrument panel
Connectivity panel	Centre console
Armrest module	Centre console
Front wheel arc	Wheel arc
Rear left uniside bracket	Bumper system
Rear left bumper bracket	Bumper system
Rear left door panel carrier	Door structure
Trunk panel	Luggage compartment
Fragrance Integration Unit	Instrument panel

3.2 Component Evaluation

After a list of potential components had been produced, next step was to collect more information about the components. After consulting with Volvo cars additive manufacturing representatives it was decided to exclude A-surfaces, the surfaces visual to the customer. These surfaces have the highest surface finish requirements, which also is one of the major issues with the FDM technology. Out of the remaining eleven components five more were eliminated due to high complexities, too large sizes or high degree of similarity to other components on the list. An example of this is the Air duct vent and the Air Duct Adapter, where the smaller and less complex one was kept.

The six remaining components were evaluated using a pugh-matrix, where the evaluation criteria were based on the desires in the requirement specification. They were all provided a weight of the total importance. This allowed some criteria to influence the result more which gave a more accurate result. The two criteria with the highest influence were load on component and production volume. The full evaluation matrix is included in Appendix A. From the evaluation matrix, two promising alternatives were identified and further investigated before a final selection was made.

The first alternative was the Air Duct Adapter. This is a special component designed to allow connection of a tube onto the HVAC-unit, which is the climate system central unit. The purpose of the adapter is to connect the HVAC to a fragrance cartridge located in the glove compartment. The cartridge distributes a scent in the car via the climate system. This component is being designed for a low volume car series of 50 cars and is not fitted on standard Volvo cars. This makes the component extra suitable for AM since producing low volume components with injection moulding is very costly. If the fragrance function was to be implemented in larger car series in the future it can be assumed to be an optional component, which means it still could be beneficial to use AM. Mechanical demands are also relatively low on this component since it is not carrying any large load nor being exposed to UV-light.

The environment where the component is located has less temperature restrictions than visible surfaces. According to the component requirement specification it should withstand temperatures from -30 to 85 °C and still be functional. Since the component is directly connected to the climate system, the need for odourless material is, however, high. Volvo Cars odour testing standard evaluates the odour on a scale with grades from 1-6 where one is "not noticeable" and 6 is "unbearable". Climate system components require a test grade of ≤ 3 in order to be approved, which corresponds to "Clearly noticeable, but not yet unpleasant". Figure 3.1 shows the CAD-model of the Air Duct Adapter.

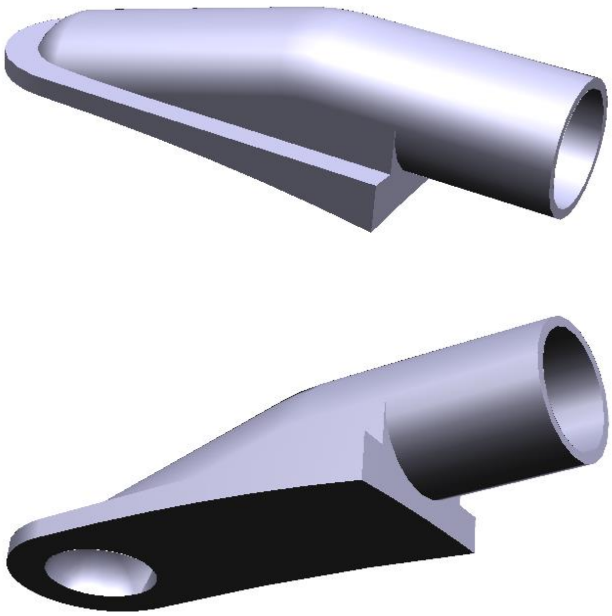

Figure 3.1: CAD-model of the Air Duct Adapter.

The second component alternative was an Integration Unit, with the function to hold two tubes belonging to the climate system in place. It is a low volume component for the same type of special vehicle described above, which makes it suitable for AM. Just as the Air Duct Adapter it is a component not visible during regular use, located behind the IP with low loading levels. The two components have the exact same requirements with the exception that the Integration Unit is not directly in contact with the climate system air flow, leading to a slightly lower demand on odourless material. A CAD-model of the component is shown in Figure 3.2.

The small size of both these components makes it unnecessary to put effort into optimizing the design to reduce weight. The weight saving potential is negligible in relation to the whole car weight. Another advantage of choosing any of these components is that they are both design to be produced with AM from the beginning. The work needed to adapt these components for manufacturing with a FDM-machine is therefore limited. Both components also have a size suitable for manufacturing in the most commonly available FDM-machines. This makes manufacturing of the component easier both with regards to manufacturing time and machine availability.

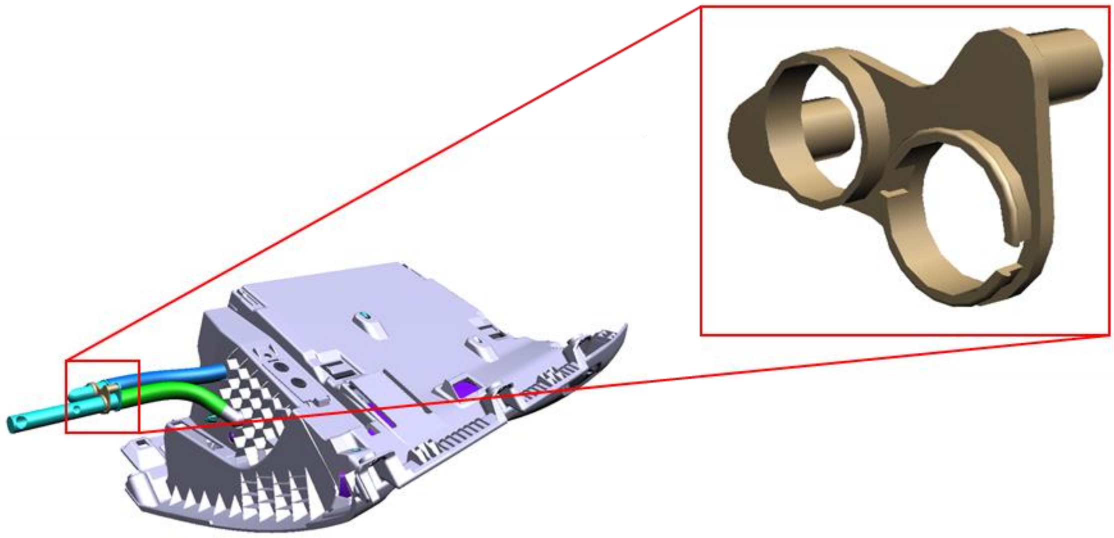

Figure 3.2: CAD model of the Integration Unit.

After evaluating which if these two components would be most suitable for the case study, the Fragrance Integration Unit was considered to have most potential. Since both components described here have more or less identical requirements, any of the two would probably have made a good case study component. The factors making the Integration Unit more suitable is the slightly simpler design in combination with less demand on odourless material.





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4 Choice of Material

To find a material suitable for manufacturing the Integration Unit, the FDM-filament market was investigated. The search was limited to recycled plastic, bioplastics and plastic bio-composites available for FDM-machines. It resulted in an overview of available material groups and it was concluded that some groups of plastics dominated the filament market. A first screening of materials was done based on the requirements on the Integration Unit. Five materials were considered to have good potential and were tested thoroughly in a lab environment. By analysing the result it was possible to decide whether the materials could meet the requirements and which of the material that was most suitable for manufacturing of the Integration Unit.

4.1 Market of Sustainable FDM Materials

After investigating the market of sustainable FDM materials it was evident that there is a trend towards more sustainable filaments. In recent years, several small firms have developed new types of plastic filaments, both from bioplastics and from recycled plastics. When looking into the larger and more established FDM material manufacturers, the offering of these types of material are, however, highly limited. The only sustainable alternative is PLA plastic which is based on bio-polymers. Due to the limited material properties of PLA, as described more in coming sections, it’s usability in engineering applications is limited. The reason why the large manufacturers, such as Stratasys, do not yet offer recycled or high performance bioplastics in their assortment is that they claim the end-quality cannot be guaranteed within reasonable cost.

Almost all of the large suppliers of FDM-machines for industrial applications today have their machines locked to certain materials. This means only material from the machine manufacturer can be used for printing in their machines. This implies that even if one of the smaller upcoming developers of sustainable material were to succeed in developing an industrial grade sustainable material, actually utilizing it in professional machines might be difficult. In this study, this issue has not been investigated further, although it is a problem that need to be considered if these types of material is to be implemented in any larger scale.

By investigating the market offerings of sustainable filaments a material list, included in Appendix B, was created. The filaments found were either bioplastics or made from recycled plastics, and a couple of them were reinforced with natural fibres. In total 53 materials from 27 different suppliers were found. The recycled filaments were ABS, PET, PLA, PETG, PA or PS. The by far most common bio-based filaments was PLA, offered by many suppliers.

4.2 Material Screening

In order to reduce the number of filaments before testing, their suitability for car applications were evaluated and plastic types currently not used in car applications were eliminated. In total 5 plastic groups passed this step: ABS, PLA, PET, PC and PS. However, PETG has similar properties as PET and was therefore included as well. Some common car applications for these materials are presented in Table 4.1. All these materials are used in cars today, although not typically manufactured with AM. Therefore, the filaments suitability for car application had to be further evaluated.

Table 4.1: Examples of usage of common FDM-materials in automotive parts.

Material	**Applications**
ABS	Dashboards, IP and interior, wheel covers, body parts, grilles
PLA	Floor mats (reinforced with nylon fibre), spare tire cover, luggage area trims (mixed with PET), upholstery material doors (mixed with PET)
PET	Interior trim, wiper arm, gear housing, headlamp retainer, engine cover, connector housing
PC	Bumpers, dashboard, lighting, panels
PS	Equipment housing, buttons, bumpers, display bases, car interior

Acrylonitrile butadiene styrene (ABS) is a plastic material with high temperature resistance and good mechanical properties. It is therefore often used in car components with different types of mechanical functions. Polylactic acid (PLA) is a bio-based plastic where the polymers are typically made from corn or sugar cane crops. The mechanical properties of PLA are limited and it is therefore most often used in components with low mechanical demands such as cover panels, floor mats and some interior trim. The material is on the other hand very suitable for FDM-processes which have made it one of the most widely used materials in desktop FDM-machines.

Polyethylene terephthalate (PET) is plastic material suitable for several different applications. The excellent water resistance and recyclability is the reason why it is used in beverage containers. It also has a high temperature resistance and relatively good mechanical properties making it suitable as engine covers, housing, and interior trim components. Polycarbonate (PC) is another high strength material. It has higher impact resistance than most other thermoplastics and is very durable. PC is therefore often used in car components such as bumpers, lighting covers and dashboard panels. Polystyrene (PS) is one of the most produced plastics worldwide. The mechanical properties are not as good as some of the other plastics described here. PS typically has a very hard surface but with the drawback that it is quite brittle. It is however used in several car components where mechanical demands are not as high. Some examples are housings, bumpers and car interior components.

Most of the filament suppliers did not have official technical material data, which made it hard to evaluate the materials suitability. After grouping by material a first elimination could be performed by looking at the available specifications. It was found that PS and regular PLA filaments did not meet the heat resistance requirement for interior components. To decide whether the temperature requirement was fulfilled or not the Heat Deflection Temperature (HDT) was used. HDT is the temperature at which the material starts to deform given a standardised load. This is not directly translatable to the temperature requirement but believed to be a good indication of the material temperature performance. The component used for the case study is required to sustain temperatures of up to 85 °C. Regular PS and PLA materials have a HDT of about 50-60 °C and were therefore eliminated. One exception was HT-PLA which is modified to have a significantly higher HDT. For ABS filaments, it could be concluded that the HDT temperature was above accepted level, and therefore ABS was of interest for further evaluation. For the remaining materials, PET, PETG and PC none or very little material data were found. PETG is a PET material with added Glycol to improve material characteristics. Regular PET was therefore discarded while PETG was passed to the next phase were the materials HDT were tested. The materials selected for further analysis is listed in Table 4.2.

The Bio-composite materials available were excluded for a couple of reasons. All fibre-reinforced materials had PLA as matrix material. They would therefore have too poor thermal properties to be used in a car interior components. Fibre-reinforce plastics also have some difficulties when it comes to manufacturing them with FDM. Due to the fibres, special types of printer components and settings are needed to achieve a good and reliable result.

Table 4.2: List of materials used for material tests.

Name	Material	Type	Supplier
Enviro ABS	ABS	Biodegradable	ThreeD materials
rABS	ABS	Recycled	Filamentive
rPETG	PETG	Recycled	Filamentive
HT-PLA	PLA	Bio-based	Add:North 3D filament
Re:Add ABS	ABS	Recycled	Add:North 3D filament

Enviro ABS is a petroleum based plastic that has been modified to be fully biodegradable. Even though the raw material source in non-renewable, a degradable plastic is more sustainable since the risk of plastic pollution in nature is greatly reduced. To get a wide range of materials covering different sustainability aspects also Enviro ABS was considered relevant for testing.

rABS is made out of recycled instrument panels, and consist of up to 90 % is recycled content. The material is, however, not entirely made out of ABS but a mixture of 60 % ABS and 40 % PLA. Another recycled ABS is Re-Add ABS consisting of about 95 % recycled material. Both filaments are made out of granulate produced of recycled ABS. The reason why no material consisting of 100 % recycled content is available is that plastic material properties degrade for each time recycled. To ensure a reliable and functional material after recycling, a small amount of virgin plastic is mixed into the material.

Another filament with recycled content is rPETG, made out of recycled plastic bottles. The recycled content is up to 90 %. The enormous surplus of PET-waste worldwide in combination with the promising material properties made it interesting for further investigation.

PLA is by far the most common bio-based filament for FDM-machines. Due to the temperature requirement only one PLA was believed to be suitable for the component in this case study. HT-PLA is a high temperature PLA which according to the suppliers have a HDT specified to 80 °C. This material is, however, not yet a commercial product but a material which properties and possibilities are currently being investigated at the Swedish filament producer Add:North.

4.3 Material Testing Procedure

In order to further evaluate the material properties, the five most promising material were tested in a lab environment. This was done both to gather general material data and to evaluate which material would be best suited for manufacturing of the Integration Unit. In this section the test procedure for each material test is described. It includes details of what has been tested and how, as well as description of what have been omitted. A total of 206 specimens in six different materials, including reference material, were tested. All results are presented in Section 4.4.

4.3.1 Printing Process Parameters

Two different machine models were used to print the test specimens in this study. To print all bioplastics and recycled materials, Zyyx+ printers were used, see Figure 4.1. This is a desktop printer with the ability to print most types of 1.75 mm plastic filaments. As reference machine, a Stratasys Fortus 380mc was used. This is a production machine intended for industrial use but with a limited number of materials available. It provide a good reference for analysis of the test results.

To translate a CAD-model into code, which can be read by the printers, a so called slicer software is used. The slicer software generates the toolpath for each layer of the print and it is there all printing parameters are entered. The slicer software used in this study was Simplify3D.

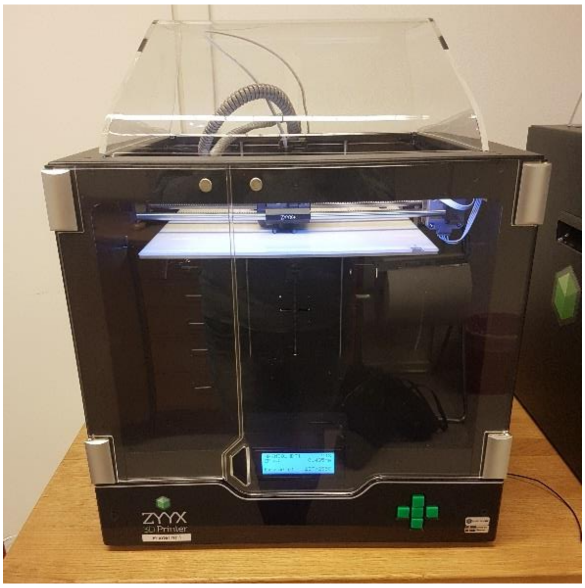


Figure 4.1: One of the three Zyyx+ printers used for printing of test specimens.

When printing a part in a FDM-printer there are several process parameters to consider. In Figure 4.2, the process parameters that could affect the printing result is listed [43] [44]. Compared to most other manufacturing methods, FDM provides a lot of possibilities in adjusting the structure of the manufactured component. By altering these parameter, widely different mechanical properties can be achieved [45].

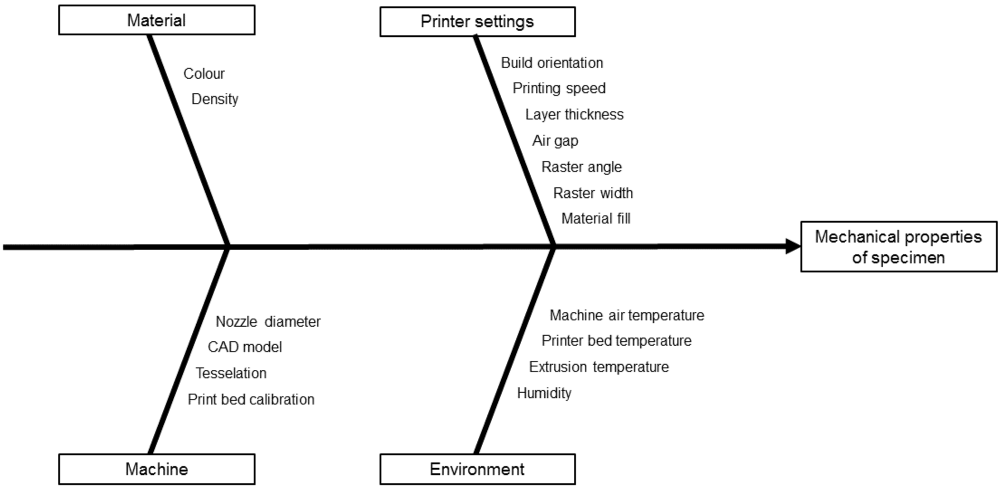


Figure 4.2: Printer parameters possibly affecting mechanical properties.

One of the most important parameters is the build orientation, which is the orientation of the printed component on the build plate, illustrated in Figure 4.3. Another important parameter is the so called raster angle. The raster angle determines in which direction the filament is being extruded relative to the component direction. To achieve a faster print, but with reduced mechanical properties, one can chose not to fill the component entirely with material. The material fill can be adjusted from a few percent up to 100 %. Other important factors are the layer thickness, raster width and air gap

[43]. Layer thickness and raster width determines the dimension of the filament string and air gap determines the distance between two parallel strings.

In this study, several different materials were tested and compared. Due to time and cost limitations it would be impossible to analyse each material with several variations in printer parameters. The only design related process parameter that was varied in these test was therefore the build orientation. For each material, test specimens were manufactured both in X-direction and Y-direction, illustrated in Figure 4.3. The Y-directed specimens were however not tested for each of the three ageing steps as further described in the next section.

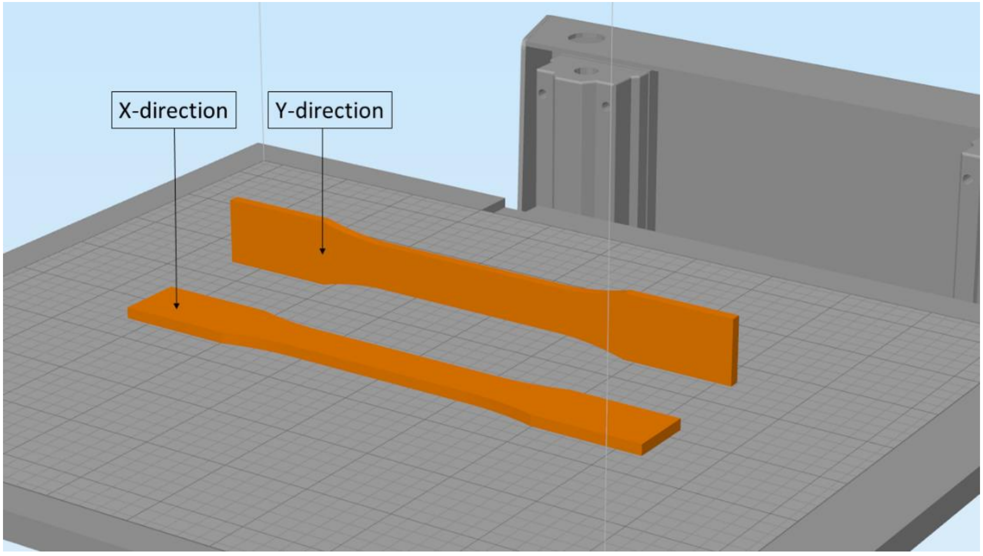


Figure 4.3: Illustration of the two printing orientations used when printing the test specimens.

To achieve as good mechanical properties as possible each specimen was filled 100 % with material. The raster orientation was fixed to 45 °/45 ° as can be seen in Figure 4.4. The same layer thickness of 0.25 mm was used for all specimens. To achieve a good print result some printer parameters were altered individually for each material. The parameters used for each material are summarised in Table 4.3. It is also important to note that no in-depth optimization of the printer parameters was done. It is possible that slightly better material performance could be achieved if this had been done. The likeliness that it would have significant impact on the final evaluation is however considered small.

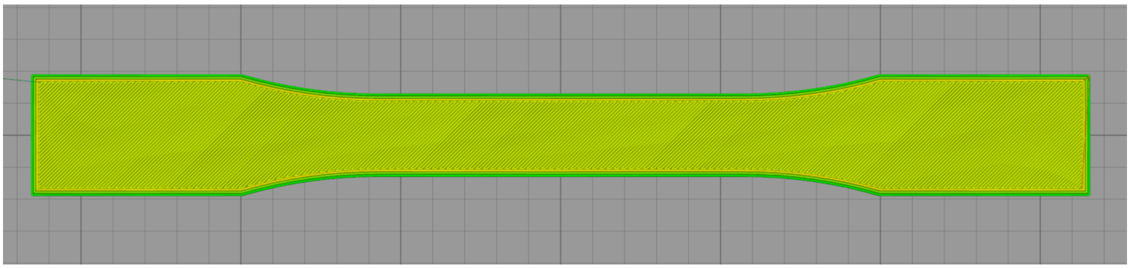


Figure 4.4: Top view of the tensile specimen viewed in the slicer software Simplify3D.

Table 4.3: Printing settings used for printing of material specimens.

Filament	Material	Extruder temp [°C]	Fan speed
ABS-M30 (Reference)	ABS	240	0 %
Enviro ABS	ABS	230	0 %
rABS	ABS	245	0 %
rPETG	PETG	230	20 %
Add:Pro HT-PLA	PLA	230	100 %
Re:Add ABS	ABS	245	0 %

4.3.2 Material Test

To gain knowledge of each material's properties a number of tests were carried out. First a Heat Deflection Temperature (HDT) test was performed to validate if the temperature resistance of the material was sufficient. Thereafter, other mechanical properties were tested by tensile, ageing and impact resistance tests, in order to find the material best suited for the selected application. Due to high requirement on low odour emissions, a test panel evaluated the odour of the materials. In addition to this, the density of each material was measured.

4.3.2.1 Heat Deflection Temperature

In order to understand how the materials perform in high temperatures, a HDT test was carried out. As defined in the ASTM D648 standard, a specimen should be loaded with a force inducing a stress of 0.455 MPa. The temperature should then be raised with 2 °C/min and the HDT is defined as the temperature where a deflection of 0.25 mm is achieved. Since the machine available for testing, a Texas Instrument DMA Q800, does not allow specimen in the size prescribed by the standard, some modifications had to be done. The maximum specimen length allowed in the machine is 50 mm compared to the 127 mm defined in the standard. For the result to be valid under ASTM conditions, the smaller specimen must deform to the same strain at 0.455 MPa stress as the ASTM standard specimen. A new load force and required deflection was therefore calculated according to a method described by the machine manufacturer [46]. For details about how this calculations was done, see Appendix C. The dimensions of the specimens used is shown in Figure 4.5.

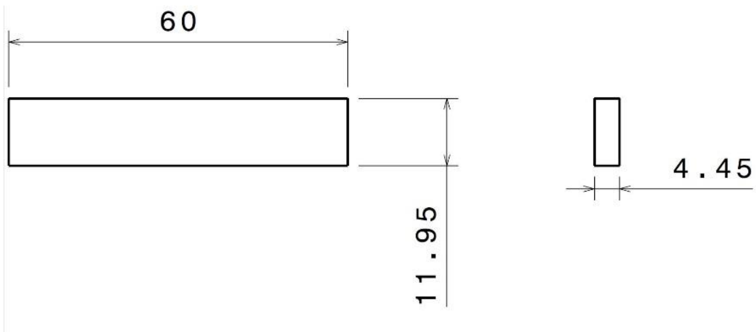


Figure 4.5: Dimensions of HDT specimen (in millimetres).

The test set-up is shown Figure 4.6. An initial test showed that the printing direction had no effect on the HDT. Hence, the specimens were only printed in the X-direction. As prescribed by the standard, two specimens were tested for each material.

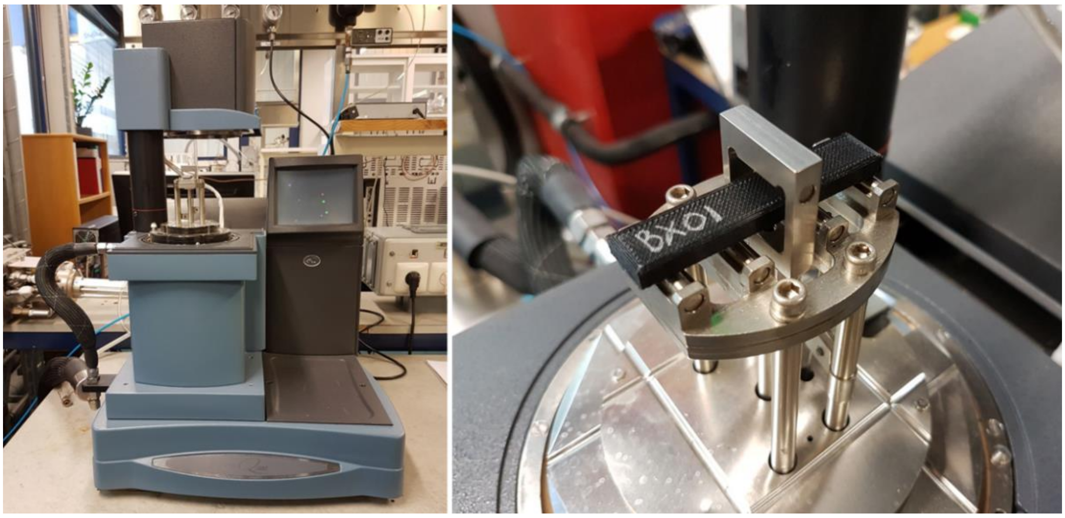


Figure 4.6: Test set-up for measuring of HDT in DMA Q800.

4.3.2.2 Tensile Strength

A tensile test was conducted in order to find basic material characteristics such as tensile strength, tensile modulus and elongation at break. The test procedure followed the ASTM D398 standard. Tensile tests are done by fixing the specimen between two clamps and applying a force in a constant speed in each end, pulling the specimen in opposite direction until the specimen breaks. By measuring the force and elongation during this process, several material properties can be calculated. A Zwick/Roell Retroline machine was used for testing which has a capacity of 10 kN. The loading rate was set to 50 mm/min. To measure the elongation an optical measuring device was used which measured the distance between two points on the test specimens. The experiment set-up is shown in Figure 4.7.

For the tensile strength test specimen, there are different types of dimensions available depending on material properties. For this test, type one was chosen which is used for specimens that have a thickness of 7 mm or less. The dimensions of the test specimen is shown in Figure 4.8. The specimens were printed in both X- and Y-direction. For each direction, five specimens were tested as prescribed by the standard.

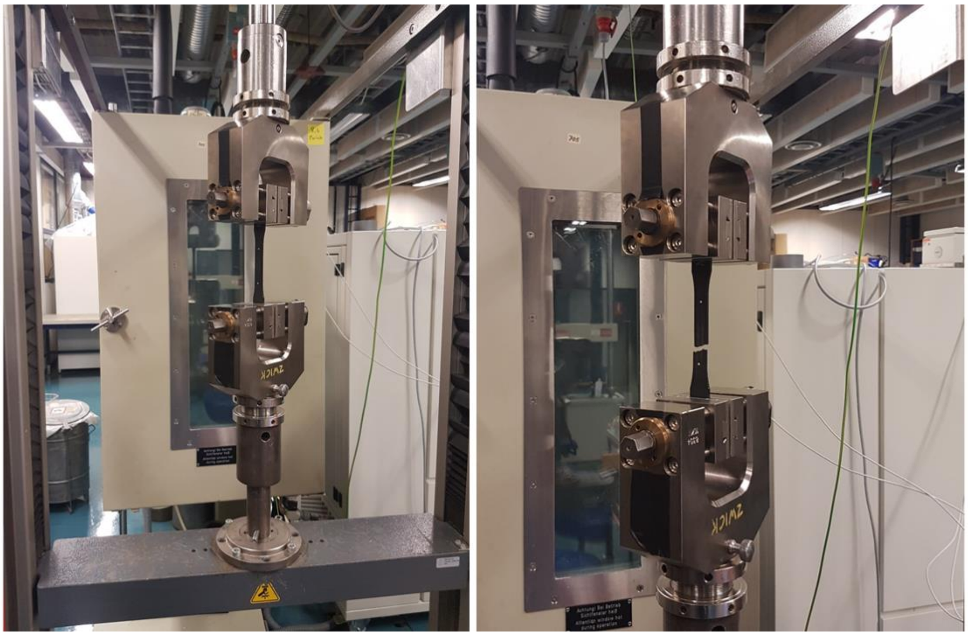


Figure 4.7: Test set-up of tensile test.

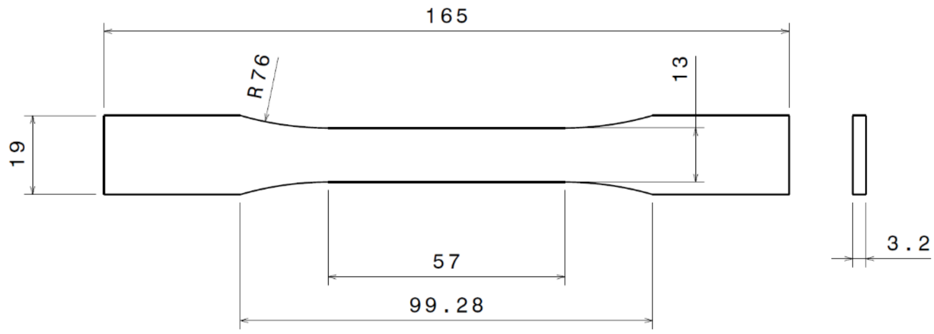


Figure 4.8: Dimensions of tensile strength specimen (in millimetres).

4.3.2.3 Ageing

To investigate how well the materials would perform over time, an accelerated ageing of the material specimens were done. Due to time limitations, this was done for the tensile test specimens in one direction only. Each set of five material specimens was aged in two different environments for 21 days. The first environment was a heat chamber with 70 °C and an air humidity of 2 % RH representing the humidity a regular indoor room. The second ageing was done in 70 °C with air humidity of 55 % RH. To ensure all specimens in each chamber would be exposed to the same conditions they were stored hanging and separated by distances as shown in Figure 4.9. After ageing, all specimens were stored in room temperature and room humidity for at least 24 hours to ensure that all tests would be conducted on materials at the same conditions. The aged materials were then tested according to the same tensile strength test procedure as for the non-aged specimens. This procedure allowed analyses of how humidity and temperature affect mechanical properties of the materials and thereby how well they are suited for car applications. The ageing test procedure is summarised in Table 4.4.

Figure 4.9: Method used for storing the specimens in ageing chambers.

Table 4.4: Specimen ageing parameters.

Ageing	Temperature [°C]	Humidity [% RH]	Time [days]
Age 1	70	2	21
Age 2	70	55	21

4.3.2.4 Impact Resistance

The impact resistance test was based on the ASTM D256 standard. The test is done by letting a pendulum fall a prescribed distance and then hitting the test specimen. By measuring the distance travelled by the pendulum after impact it can be calculated how much energy was absorbed by the material. Some modifications to the standard method was done to adapt it for the available test equipment. The specimens were placed laying down instead of standing up, as described in the standard. Also, as shown in Figure 4.11, the specimens were notched on both sides instead of just one. The experiment set-up is shown in Figure 4.10. The pendulum used had an impact blow of 40 kpcm (0.981 J). The specimens were printed in both X-direction and Y-direction, since the mechanical properties were expected to differ between these two set-ups. In total 5 runs were carried out for each material and orientation respectively.

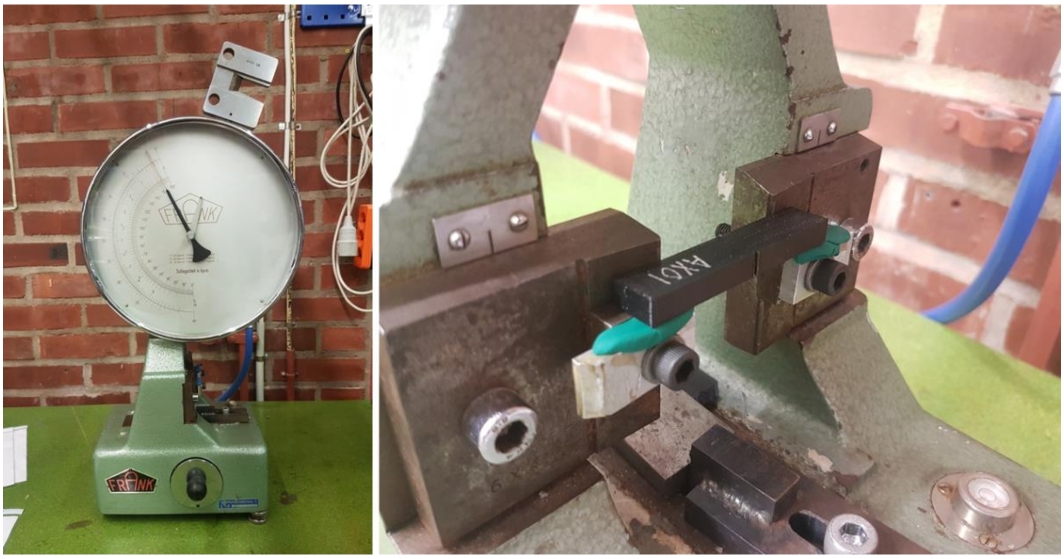


Figure 4.10: Test equipment and experiment set-up for impact resistance test, where the pendulum rotates around the scale and hits the notch of the specimen.

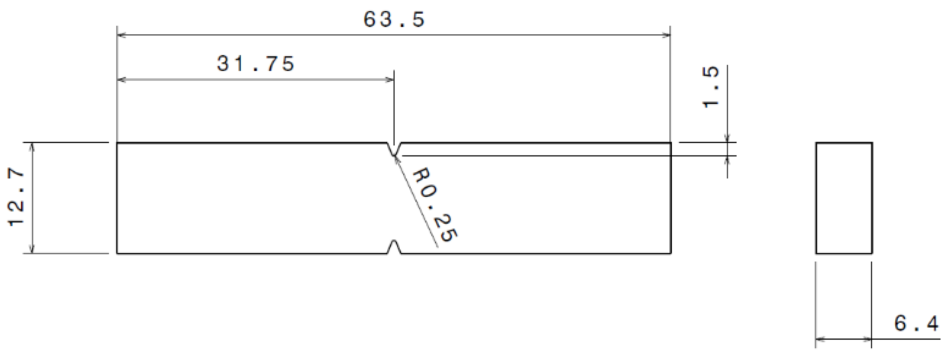


Figure 4.11: Dimensions of the pendulum impact resistance test specimen (in millimetres).

4.3.2.5 Density

To measure the density of each material a Mettler Toledo AX2014 density measurement machine, see Figure 4.12, was used. The machines measures the weight of a material specimen first in air and then in ethanol liquid. By using these two measurements the density is calculated based on the buoyancy of the material. The accuracy of the measurement is 0.1 mg. Two specimens were tested for each material and the average density was then calculated.

Figure 4.12: Test equipment Mettler Toledo AX204 used to measure material density.

4.3.2.6 Odour

In a car environment the climate is of high importance, which is why high odour constraints for materials exist. The procedure described in the Volvo Cars standard VCS 1027, 2729 was used to identify the odour level of each material under the impact of increased temperatures and moisture. For each material, two samples with a volume of 20 cm^3 each, were placed in 1 litre vessels, one with water and one without. After sealing the vessels they were placed in heating chamber measuring 40 °C for 24 hours. The odour test was performed right after the 24 hours had elapsed, where four assessors evaluated the odour based on a scale with six grades, see Table 4.5. It was possible to rank between two grades giving a total of 11 levels.

Table 4.5: Grades used in the standard scale for evaluating odour.

Grade	
1	Not noticeable
2	Noticeable, but not unpleasant
3	Clearly noticeable, but not yet unpleasant
4	Unpleasant
5	Highly unpleasant
6	Unbearable

4.3.2.7 Industrial Printer Reference

Since it was not possible to print the new materials on industrial printers, it was of interest to investigate how much the choice of printer affected the test results. By choosing a reference material, ABS, it was possible to print the same material on both an industrial FDM-printer and the FDM-printer used for the other materials. The reference machine used was a Fortus 380mc from Stratasys.

The original component was planned to be produced in an SLS printer in PA12 material. After consulting with AM responsible at Volvo Cars, ABS was considered the best alternative to PA12 for FDM-printing. By performing all test presented in section 4.3.2 it was possible to analyse what implications the choice of printer had on the measured material properties. The result was used to reason weather the materials could have performed better if an industrial printer was to be used. This also provided a reference towards which the material properties could be compared. The ABS plastic used in this comparison is an industrial-grade plastic from Stratasys named ABS-M30.

4.3.2.8 Material Structure Analysis

To analyse the material structure of the materials a microscope was used. The fracture surfaces after impact resistance tests were investigated for the reference material printed in the Fortus machine and for the Re:Add ABS material printed in the Zyyx. By doing this, the material infill amount could be evaluated as well as the bonding between extruded layers. This information was then used when analysing and explaining the material properties achieved in the two different machines. The equipment used was a Leica M205 C microscope seen in Figure 4.13.

Figure 4.13: Microscope used for material structure analysis.

4.4 Test Result

In this section, all test results are presented. The results are presented in the order in which they were attained. The results were continuously used to eliminate non-feasible materials which is why the number of remaining materials decreased throughout the process.

4.4.1 HDT

The result from the heat deflection temperature test was compared to the temperature requirement of 85 °C. Figure 4.14 shows the results, where it could be concluded that neither the rABS, rPETG nor the HT-PLA managed to reach above 85 °C. Since HT-PLA had such a low HDT it was ruled unsuitable for the Integration Unit. For that reason, the material was excluded from the subsequent material tests.

The remaining specimen were closer to the temperature limit and could for that reason not be immediately excluded. It should be mentioned that the requirement of 85 °C is the maximum temperature the component should be functional in. This temperature is not directly related to the HDT. A component may well be functional even at a temperature above the HDT, depending on application and how the component is loaded. The load on the Integration Unit is very limited. Hence, and a HDT slightly lower than 85 °C might still be acceptable. For that reason, no additional material could be excluded solely based on the HDT results.

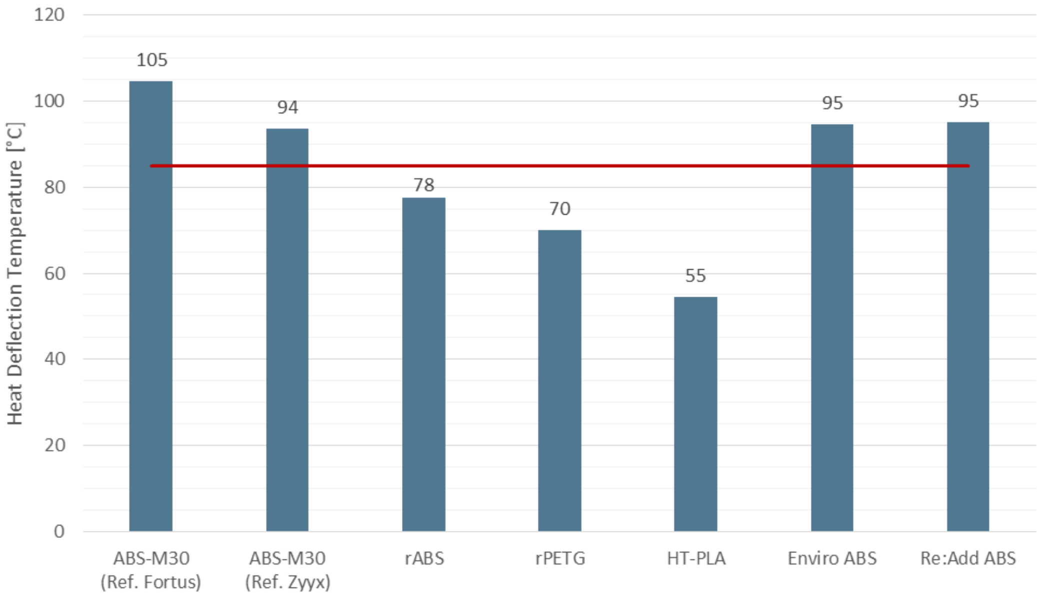


Figure 4.14: Results from HDT measurements with component temperature requirement marked in red.

It was expected that all ABS material would have about the same HDT. As evident from the results, all ABS materials except the rABS do have a HDT of around 95 °C or above. The reason for the lower temperature on the rABS is likely that the material is a mixture between ABS and PLA. The material consists of 40 % PLA which explains this reduced thermal properties.

The graphs showing the detailed measurement results can be seen in Appendix D. They show that the two measurements done for each material show very similar results in all cases. The maximum variation measured between any two specimens of the same material was 1 °C.

When it comes to the difference between the two references, a much more similar results was expected. The material used is identical and the HDT should therefore, in theory, also be identical. To investigate the cause of this difference further tests were conducted. By running Differential Scanning Calorimetry (DSC) on the two materials it was concluded that the two reference materials had different thermal history. This is illustrated by the peak on the blue curve in Figure 4.15. On materials with identical thermal properties one would expect the two curves (red and blue) to coincide more or less completely.

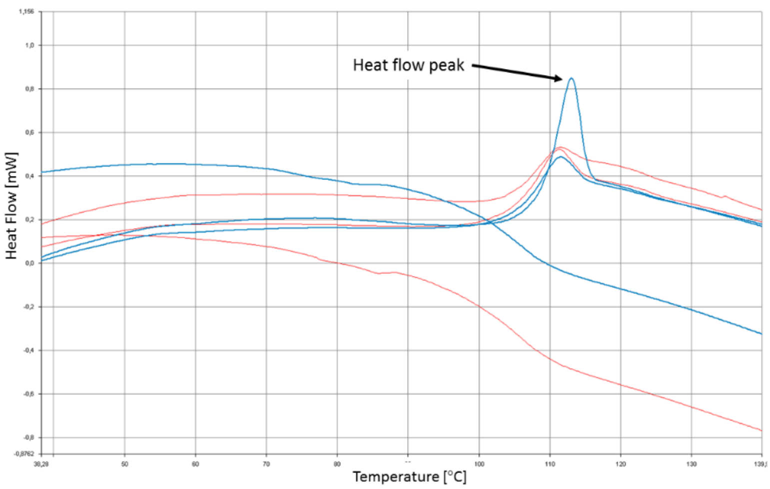


Figure 4.15: Result from DSC measurement showing the heat flow for material A (Blue curve) and material B (red curve).

This difference can likely be explained by the fact that the Fortus mc380 prints the components in a heated environment while the Zyyx+ prints in room temperature. The heated environment results in a slower cooling of the part and thereby a different microstructure in the material. To further assess this possibility, two new specimens, one for each material, were stored in 70 °C for 18 hours and then cooled to room temperature at the same rate. The two specimens were in that way exposed to the exact same heating and cooling procedure. A new HDT measurement was then done on both specimen. The results showed a HDT of 105 °C and 101 °C on the Fortus reference and the Zyyx reference respectively. The two materials had a much more similar HDT and it is likely that an even closer result could be obtained if the materials were annealed longer or at a higher temperature. From this investigation it can be concluded that the two AM-machines affects the materials in different ways. As will be discussed below, this will likely have some sort of impact also on the mechanical test conducted on the materials.

4.4.2 Tensile Test

By conducting tensile tests on specimens in both X- and Y-direction it was possible to draw conclusions on how the print orientation affected the tensile strength, elongation and tensile modulus. Overall, the test results in X-direction were more stable with less variation. Y-direction specimens generally had higher tensile strength.

4.4.2.1 Tensile Strength

Tensile strength is a measurement on how large stress a material can withstand before plastic deformation occur. Most often, this is also the same as the yield strength. In Figure 4.16 the average result is presented for each material together with a 95 % confidence interval. The low variance in both X- and Y-direction indicates a consistency in the testing and printing process. In X-direction it can be seen that all materials performed better than the reference, while the results in Y-direction varied more. The pervading higher values in Y-direction show that the print direction, as expected, significantly affect the strength of the materials. One explanation for this could be that more layers are added when printing in Y-direction, resulting in more material strings parallel to the tensile test pulling direction.

The reference specimens from the Fortus and Zyyx printers got similar results in X-direction, however, the Zyyx gave higher tensile strength in Y-direction. This behaviour might be caused by the different print environments explained in section 4.4.1. However, this theory implies that the same trend is expected in X-direction. The similar values in X-direction is in that way contradicting the theory and makes it hard to draw any conclusions why this result is seen. Whether print direction and print environment are influencing factors or not could not be decided without further testing.

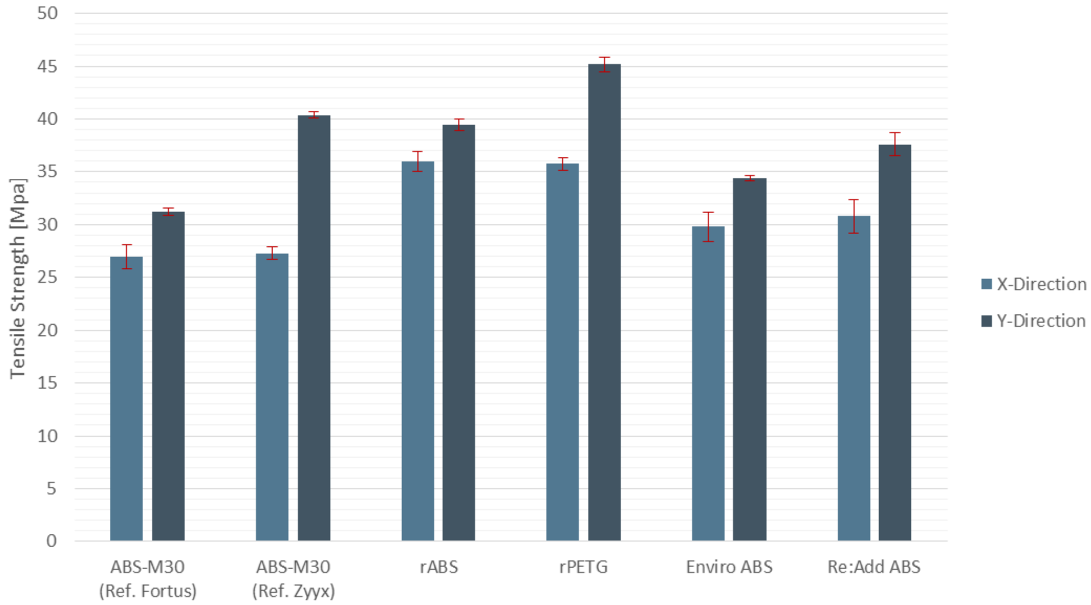


Figure 4.16: Test results of the tensile strength measurements with error bars representing 95 % confidence interval.

4.4.2.2 Elongation at Break

The elongation at break measurements showed large variations for most materials. As shown in Figure 4.17, the variation is particularly large for the rABS and rPETG printed in Y-direction. One explanation for this could be that some specimens fractured outside the measurement interval. For the rABS this was due to stress concentration at the radii which is a result of the printing of radii layer by layer. This is shown in Figure 4.18. An even larger variation was found for rPETG, in Y-direction, to an extent where no significant results can be drawn related to the other materials. The rPETG specimens in Y-direction had very varying fracture behaviour. Some specimens fractured like a brittle material while some other fractured very ductile. The two different types of fracture modes are shown in Figure 4.19. Even though no explanation to this behaviour was found it can be concluded that this uncertainty is problematic when it comes to material reliability.

When comparing the two reference materials one can conclude that the Fortus mc380 has a more stable process indicated by the smaller confidence interval. The Fortus material also appears to be more ductile than the one printed in the Zyyx machine. The results could be linked to the print different cooling processes discussed in section 4.4.1. But drawing any definite conclusion on the explanation for this result is not possible based in the measurement done here.

Comparing the other materials towards the reference shows that a larger variation is present for all ABS materials. The rPETG in X-direction, however, has a very low variation, even lower than the Zyyx reference. Another noteworthy difference is the higher ductility of the rABS compared to the other ABS materials. This could be explained by the fact that this material is made out of a mixture with 40 % PLA and 60 % ABS.

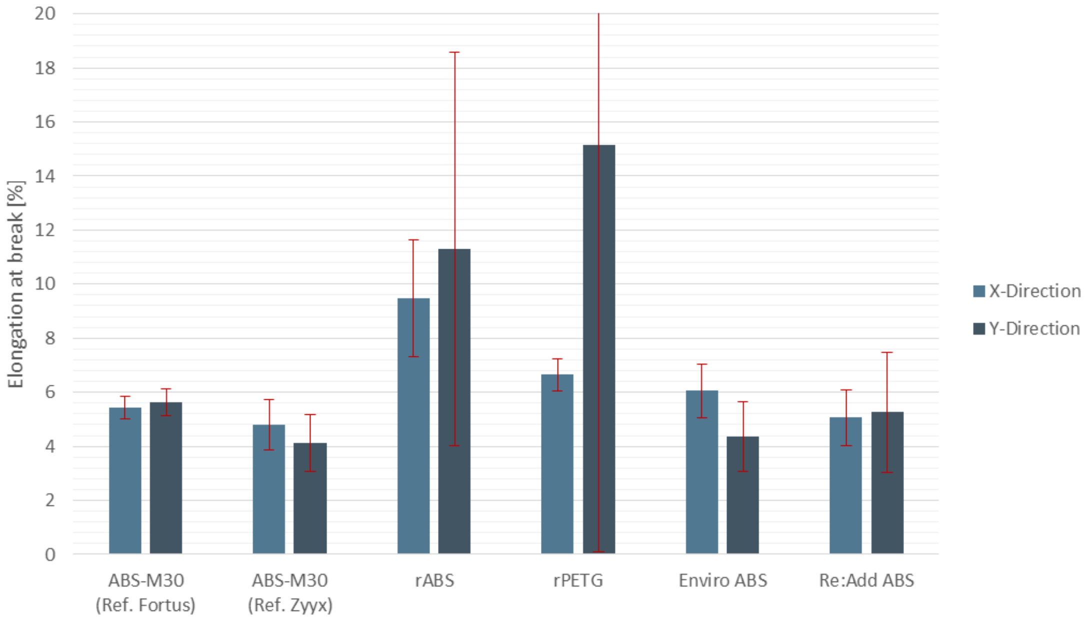


Figure 4.17: Measurements of elongation at break from tensile test with error bars representing 95 % confidence interval.

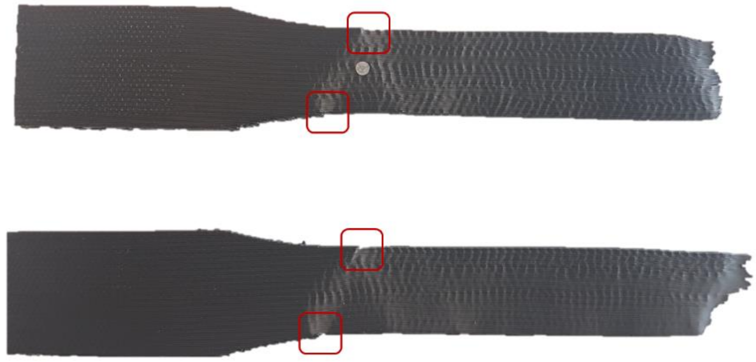


Figure 4.18: Tensile test specimens of rABS printed in Y-direction. Stress concentration areas marked in red.

Figure 4.19: Tensile test specimens of rPETG showing a brittle fracture (upper) and a ductile fracture (lower).

4.4.2.3 Tensile Modulus

The results from the tensile modulus measurement, see Figure 4.20, indicates that print direction affects the result. Y-direction perform better than X-direction, which is pervading for all tested materials. When looking at the X-directions, all confidence interval coincide which means no material performed significantly better or worse than any other. Looking at the Y-direction, the best performing material was the Re:Add ABS. The variation is similar for all materials tested with no material performing much better or worse than the other, however, Y-direction is slightly more stable than X-direction in general.

No differences can be verified between the two reference materials. Also the variation is similar for the two machines. This indicates that the choice of printer has little or no effect on the resulting material tensile modulus.

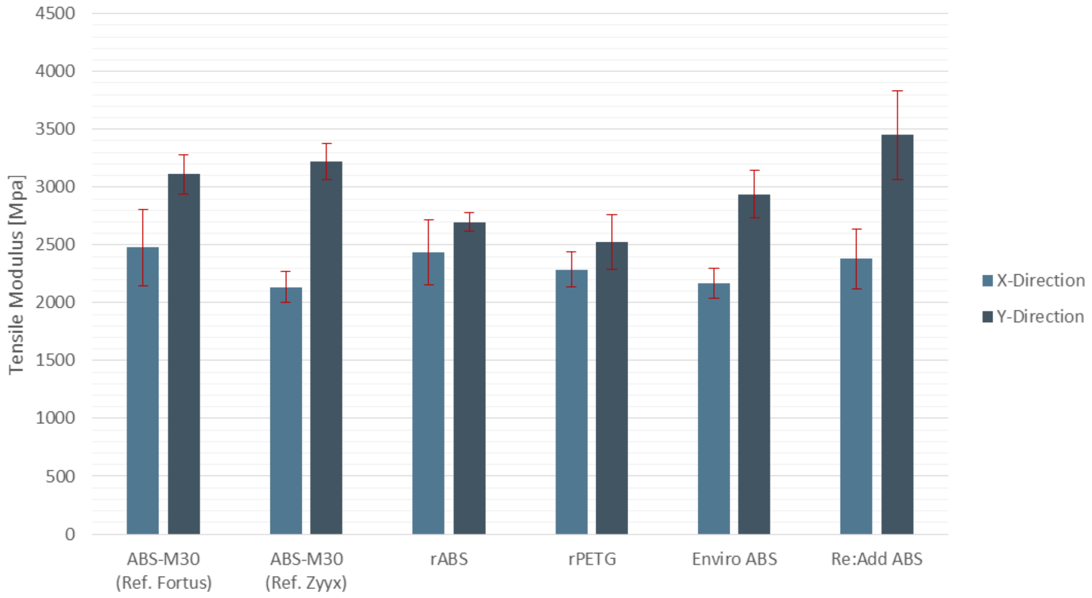


Figure 4.20: Measurements of tensile modulus with error bars representing 95 % confidence interval.

4.4.2.4 Ageing

From comparing the tensile strength of the materials after being aged in two different environment, as seen in Figure 4.21, it is clear that ageing has very little effect on the material properties. With one exception, all ABS materials perform equally well without showing a significant reduction in tensile strength after any of the two ageing procedures. The exception is the Zyyx reference material which appears to have increased tensile strength after ageing in 70 °C and 55 % RH. Since this effect was not seen on any other specimens, and is not what you expect, it is believed to be an outlier. Looking at the rPETG material it shows a slightly reduced performance after the high humidity ageing. The difference is statistically significant although just slightly.

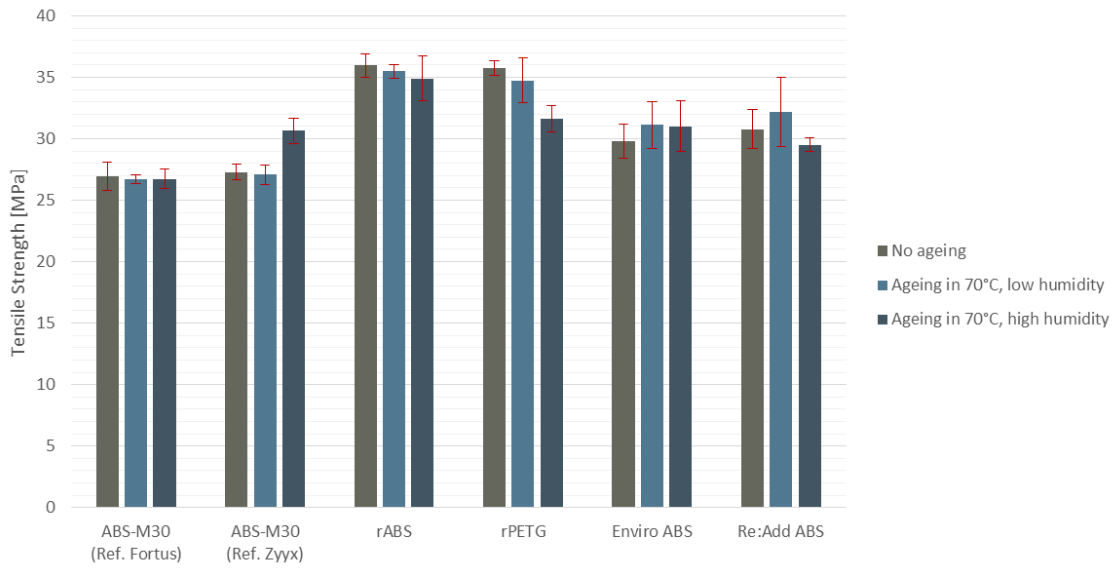


Figure 4.21: Result from tensile strength measurements comparing the materials after three different ageing procedures with error bars indicating 95% confidence interval.

The tensile modulus seems to be affected more by ageing than the tensile strength did. As shown in Figure 4.22, the tensile modulus is increased for the Zyyx reference, rPETG and Re:Add ABS after ageing. Considering the relatively large confidence intervals it is possible that the same effect is present for more of the materials although not shown with any significance here. One theory to why this effect is seen is that the high temperature exposure function as a type of material annealing resulting in a higher tensile modulus. The high humidity could, in turn, be softening the material which would explain the generally slightly lower modulus after the high humidity ageing compared to the low humidity. If excluding the Zyyx reference in high humidity, which was assumed to be an outlier earlier, this tendency is seen throughout most materials but not always with statistical significance.

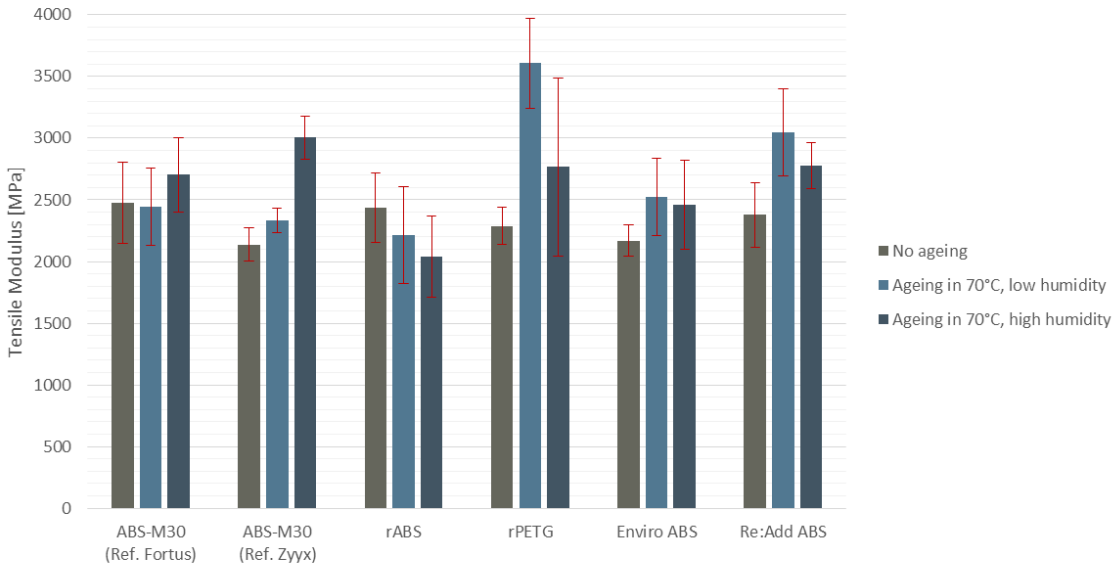


Figure 4.22: Result from tensile modulus measurements comparing the materials after three different ageing procedures with error bars indicating 95% confidence interval.

Summarising the ageing test it is clear that none of the material, with the possible exception of rPETG, performed worse after ageing in 70 °C and 55 % RH for 21 days. Considering the choice of material this was also the expected result. All materials investigated are commonly used in applications with high humidity and high temperatures. This test shows that the FDM-process does not reduce these material properties. Going forward in the material analysis these result will for that reason not have any effect on the actual material choice.

4.4.3 Impact Resistance

The impact resistance test showed varied results as seen in Figure 4.23. In general, the results indicate that print direction has no or very little impact on the impact energy absorption. rABS had the largest difference in X-and Y-direction, however, not large enough to be statistically significant. rPETG absorbed around 50 % less energy than to the Zyyx reference, while Enviro ABS outperformed the Zyyx reference with more than doubled the energy absorption. For the recycled ABS specimens (rABS and Re:Add ABS) no statistically significant difference was identified in either direction when compared to the reference.

Overall, the confidence intervals indicated a normal variation between the specimens with one exception, Enviro ABS. The large variation is believed to a result of irregularities in the material. It might be a result of poor printer settings or variations in the filament material itself. It is also worth mentioning that this type of test is very sensitive to material defects and an outlier in the results is therefore not very unlikely.

The Zyyx reference absorbed more energy than the Fortus reference. An unexpected result considering the elongation at break results which showed a larger ductility in the Fortus reference. In general, a more ductile material would absorb more energy at impact. However, the test result should be studied critically even though a significant difference between Zyyx and Fortus is observed. The relatively small difference in energy absorption in both X- and Y-direction makes it hard to draw conclusions of the behaviour seen in Figure 4.23. Since all materials broke relatively easy it could be of interest to look at how a lighter pendulums would affect the result.

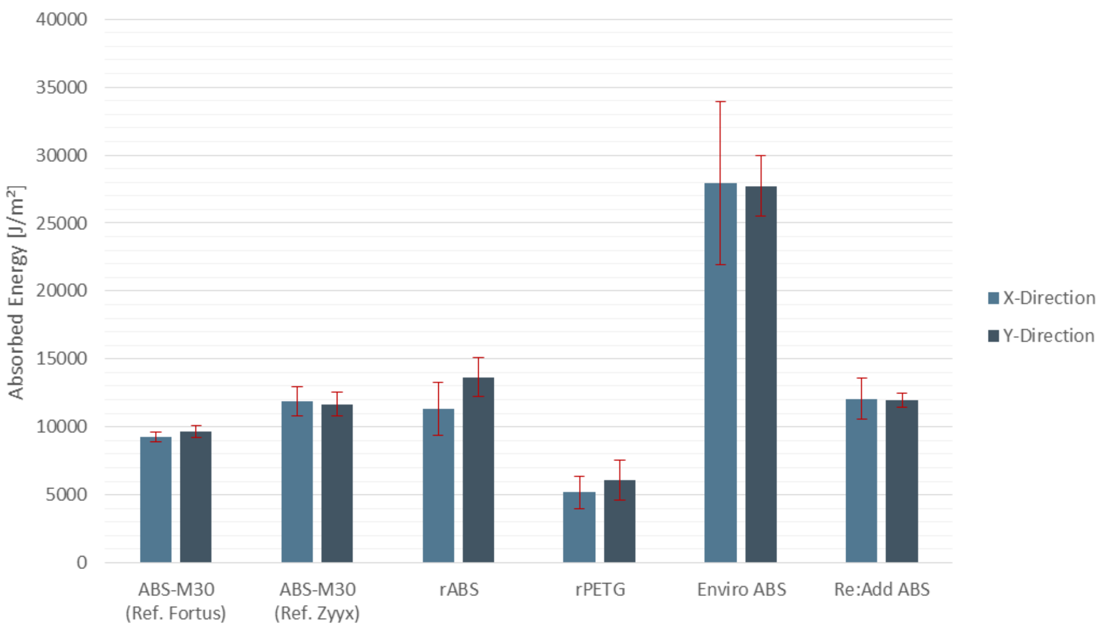


Figure 4.23: Results from impact resistance test with error bars representing 95 % confidence interval.

4.4.4 Density

The measurement of material density showed results similar to what was expected. In general, the measured densities were slightly lower than the solid densities for the materials tested. This could be a consequence of the AM-process in itself which might lead to a not 100 % material infill. All results are summarised in Figure 4.24.

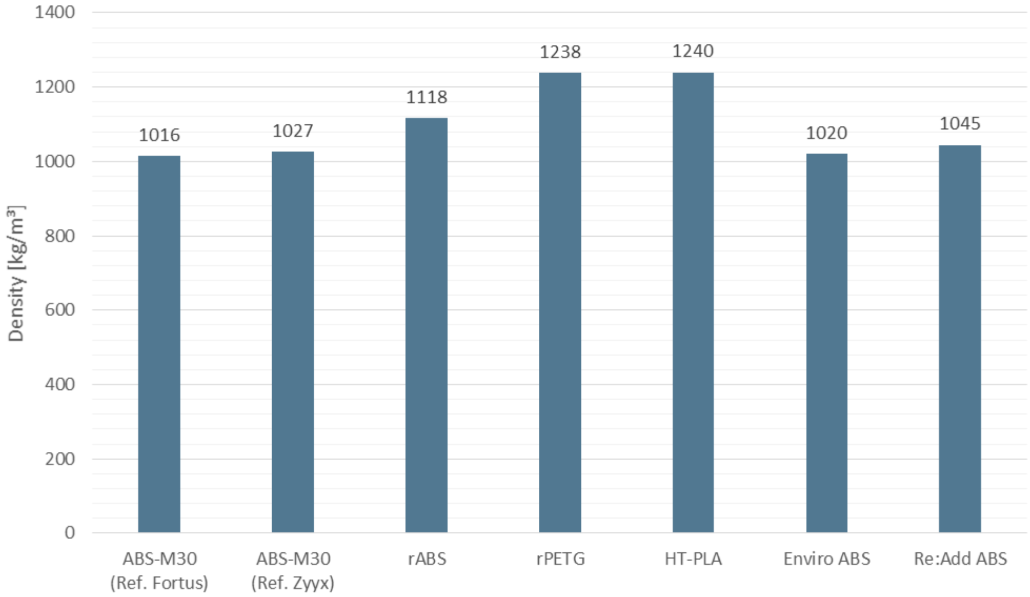


Figure 4.24: Results from density measurements.

4.4.5 Odour

The odour test results are based on subjective assessment of an expert panel where individuals rank material odour. Odour tests are suitable for comparison between materials, while specific grades should be used with precaution. All tests except one had a variation between 0.5-1.5 units and one had a variation of 2 grade units. In order for the test to be approved the variation needs to be less or equal to two grades, which was fulfilled.

For the material to pass the test the average score must be ≤ 3, corresponding to “noticeable but not yet unpleasant”. As seen in Figure 4.25, the only sample immediately passing the test was rPETG. Both rABS and Enviro ABS were disqualified immediately based on their high odour results. Re:Add ABS did not pass the test, however, a slightly higher grade than 3 can be approved in certain cases where the higher grade do not affect the driver nor the passengers. Higher grade have been accepted for small components either hidden or placed behind interior panels. Since the mentioned criteria correspond well with the Integration Unit rPETG and Re:Add ABS were considered suitable materials.

Comparison between the Fortus and Zyyx printed specimen showed marginally higher odour levels from the Zyyx specimen. More similar results was the expected outcome since the specimen consist of the same material. Whether the variation is caused by their different print environment or other circumstances is hard to conclude. Assuming that ABS components manufactured in the Fortus machine in general has a lower odour level than components manufactured in the Zyyx machine, some wider conclusions can be drawn. The Re:Add ABS would in that case get a better result if manufactured in the Fortus. Giving even further reasons to not exclude it based on the odour result at this point.

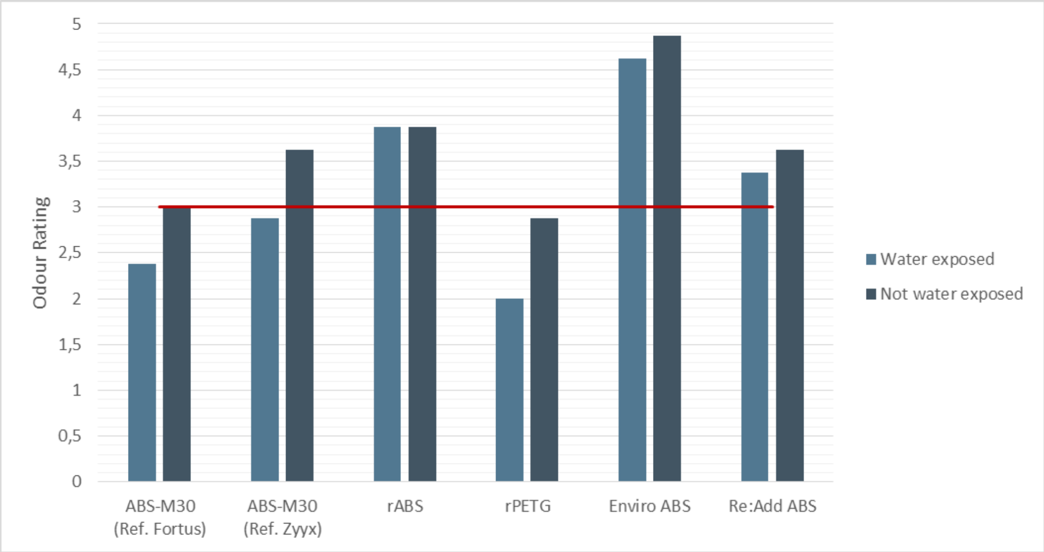


Figure 4.25: Result from odour test with maximum accepted level marked with red line.

4.4.6 Material Structure Analysis

The material structure was analysed on the Fortus reference ABS material and the Re:Add ABS material. For each material and print direction, two pictures were taken in a microscope to show the fracture surface of the specimens after the impact resistance test. All pictures are taken on the specimens in the same direction to allow easier comparison. This means that the X-direction specimens shown here were printed from the bottom up, from the picture perspective, and Y-direction specimens were printed from left to right.

The Fortus reference material, printed in X- and Y-direction is shown in Figure 4.26. As evident from the pictures, the difference in print orientation has profound impact on the material structure. The specimens printed in Y-direction appears to have a much denser material fill in most areas. The X-direction, on the other hand, has a more evenly distributed infill with less variation across the surface.

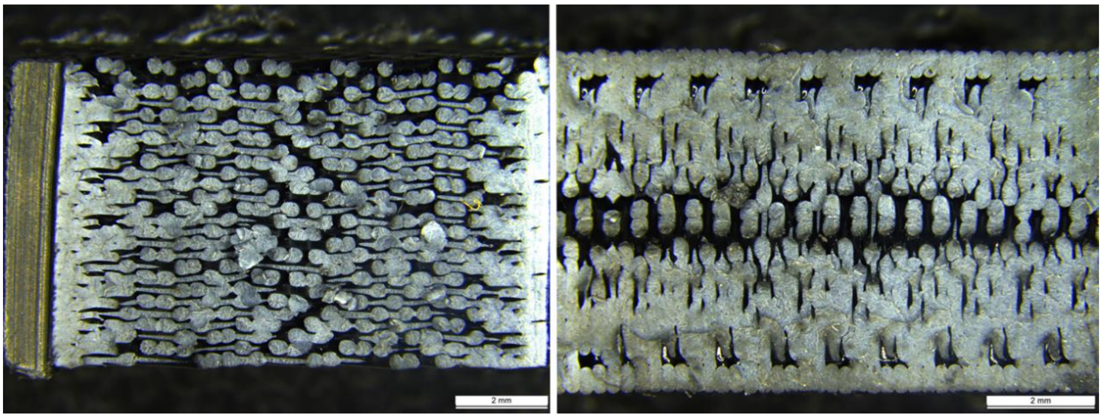


Figure 4.26: Pictures of Fortus reference specimens printed in X-direction (left) and Y-direction (right).

In Figure 4.27 and Figure 4.28 respectively, more detailed pictures of the two specimens are shown. Here it is clear that the adhesion between strings of material differ throughout the surface. Close to the edge of each material layer, an almost solid structure is achieved. Further away from the edges, the strings are more separated. The effect is present in both directions but it appears to have different practical effect depending on print direction. Since a larger fraction of the total surface is close to the solid edge in the Y-specimens, a larger part of the total cross section area is close to solid. This might be one of the explanations to why the specimens printed in Y-direction generally performed better on the mechanical material tests.

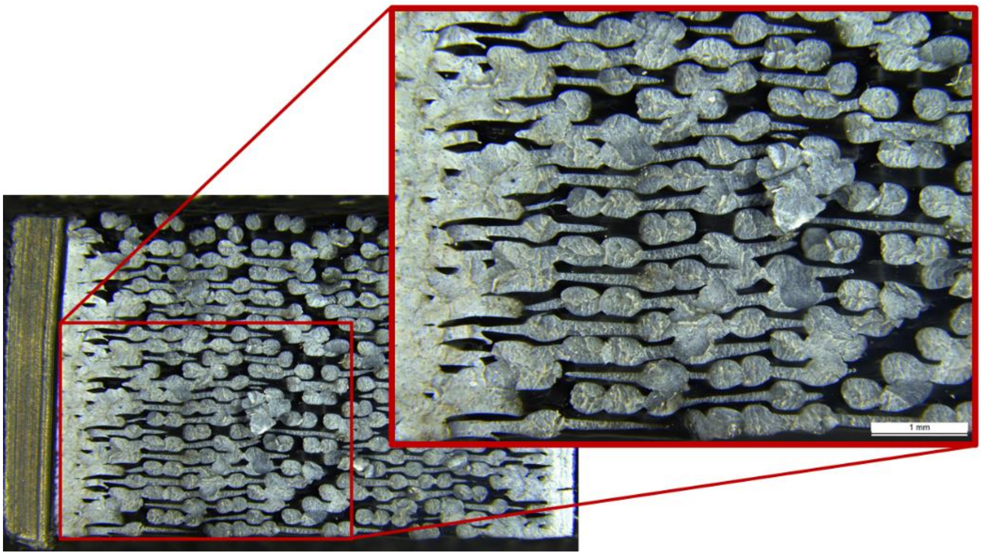


Figure 4.27: Detailed section of the Fortus reference material printed in X-direction.

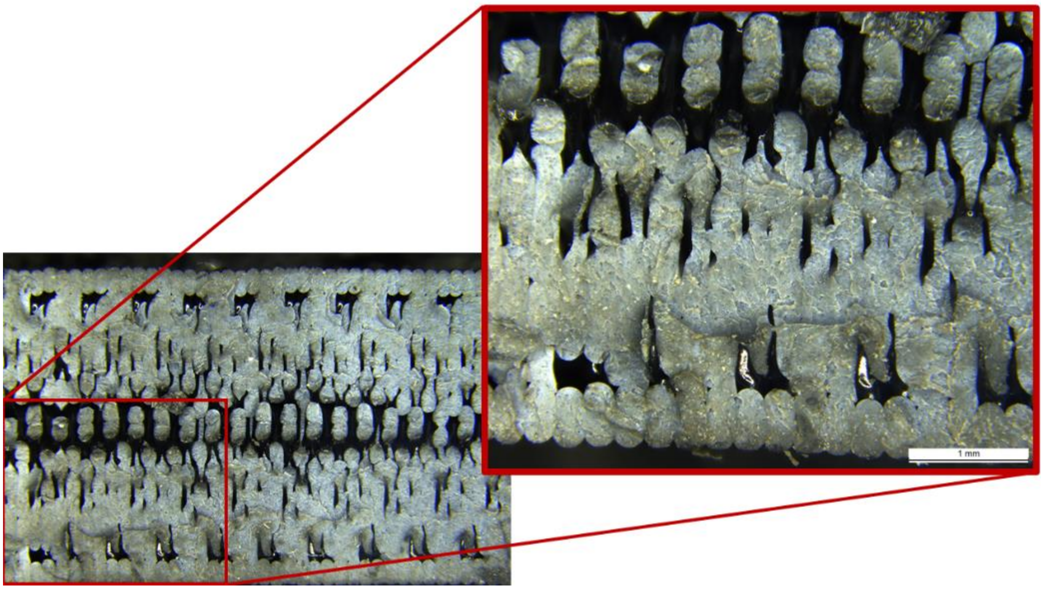


Figure 4.28: Detailed section of the Fortus reference material printed in Y-direction.

Figure 4.29, showing the fracture surface of the Re:Add ABS specimens printed in X- and Y-direction respectively, is not as easily interpreted as the previous examples. A large part of the surface is rough and appears solid. Whether this is a result of better material bounding between layers or an effect of the actual material fracturing is not clear. Based on what can be seen “under” the blurry surface one can conclude that the material appears to be more evenly distributed. It also seems like the edges differ much less from the centre of the surface than shown in the Fortus reference. On the border, especially in Y-direction, it appears to be less bounding between layers in the Re:Add ABS material compared to the reference.

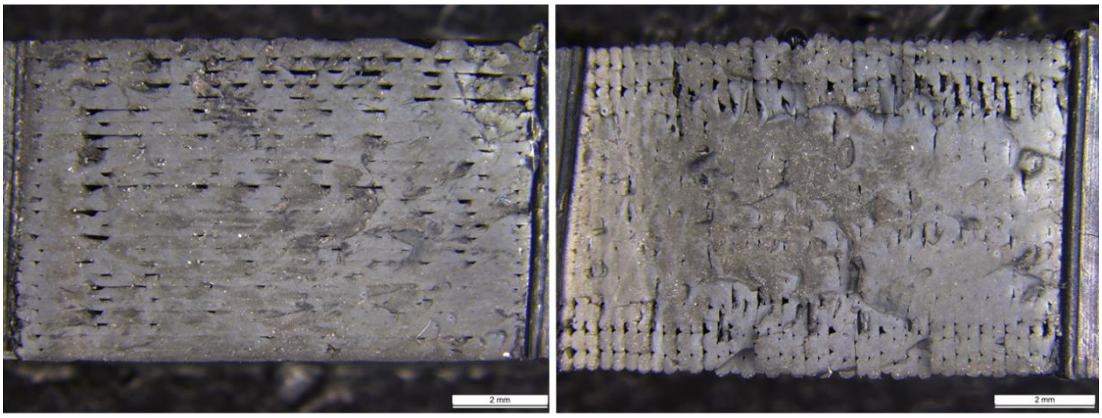


Figure 4.29: Pictures of Re:Add ABS material specimens printed in X-direction (left) and Y-direction (right).

From the more detailed picture of the X-direction in Figure 4.30 it is evident that the layer bonding varies between different layers. Some layers appears to be very well bounded while a clear gap is shown between others. It also appears to be a difference across each layer, with better bounding close to the edges and not as good closer to the centre of the specimen. In Figure 4.31, showing the Y-direction, the same effect is shown although to a slightly lower degree. This might be another explanation to why the Y-direction specimens performed better in most of the test. Even if differences between the two printers are obviously present, further investigation would be needed to fully understand the practical implications. The differences does, however, provide some indication to why significant differences are seen between the two printers in the mechanical testing.

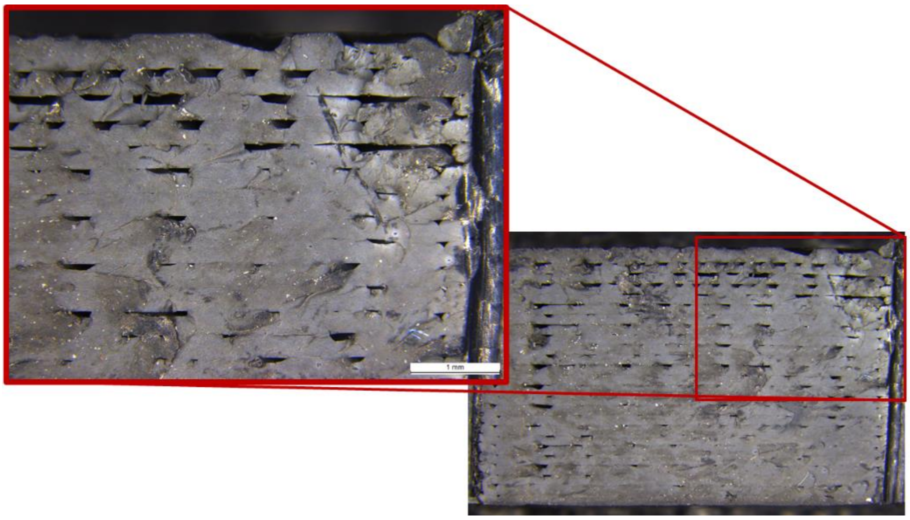


Figure 4.30: Detailed section of the Re:Add ABS material printed in X-direction.

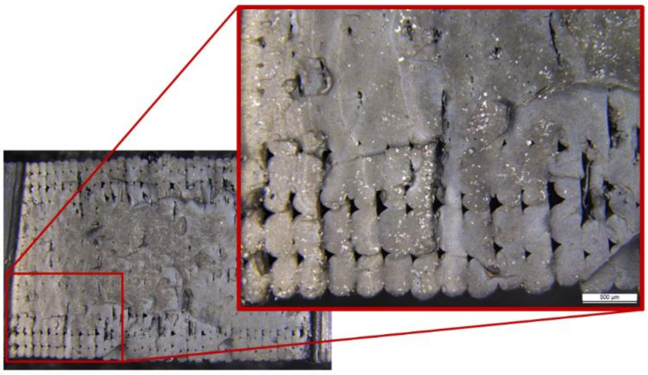


Figure 4.31: Detailed section of the Re:Add ABS material printed in Y-direction.

4.5 Conclusion

From the material tests conducted it can be concluded that, as expected, the choice of printer and printing direction will affect the end result. The industrial Fortus reference machine generally gave more stable and reliable results while more variation was seen from on the Zyyx+. The geometry of parts printed in the Fortus was also better and more reliable. When it comes to mechanical properties it is not, however, entirely clear that the Fortus prints better parts. Both the tensile strength and absorbed impact energy was similar when comparing the two references. The Zyyx even tend to perform better in some aspects. The reason for that cannot be fully understood based on the measurements done here, but some possible explanations have been found. One of the most probable is the heated chamber in which the Fortus machine prints. Measurements have shown that the thermal properties of the two reference materials differ, likely explaining the higher HDT value for the Fortus material. Probably this has effect also on other parameters which might explain some of the differences described above. Considering the low number of tests done on each material the results should be seen as indications rather than the absolute truth. They do however raise some interesting questions worth investigating further.

Comparing the different recycled plastics and bioplastic it can be concluded that the overall best result was that of the Re:Add ABS. A high HDT in combination with good performance both on the tensile strength and impact resistance makes it the best overall performing material with regards to thermal and mechanical properties. The performance in the odour test was among the best even though a slightly too large value was received. Considering the application of the case study component it is still considered a sufficient result. The ageing tests showed no reduction in performance which indicates good material functionality over the whole usage phase. The test results are summarised in Figure 4.32.

Available bio-based alternatives do not yet show mechanical properties good enough for car applications. The bio-based PLA material tested here, which was modified to withstand higher temperatures, still performed way to low on the HDT measurements.

Test	ABS Zyyx+	Enviro ABS	rABS	rPETG	Re:Add ABS
HDT	REFERENCE	0	-	-	0
Tensile		0	0	0	0
Ageing		0	0	-	0
Impact resistance		+	0	-	0
Density		0	0	-	0
Odour		-	-	+	0

Figure 4.32: Showing the performance of the materials compared to the reference, where the total performance is based on the test result and the reliability of the test result.

5 Sustainability Assessment

From the material tests the Re:Add ABS was considered the most suitable choice of plastic. To evaluate how the material performed compared to the reference from a sustainability perspective, a sustainability assessment was conducted. In this assessment, the bio-based PLA was evaluated as well, in order to gain knowledge of how recycled, bio-based and virgin plastics differ from a sustainability perspective. The results provided information used to decide whether the Re:Add ABS was the best suited material also from an environmental perspective.

5.1 Method

To analyse the environmental impact of the Integration Unit component when manufactured with PLA and Re:Add ABS respectively, a life cycle perspective was used. The total energy consumption and CO_2-equivalent emissions throughout the life cycle of a single component was compared to the corresponding values of the reference virgin ABS material. In addition to this, the emissions of NO_x and SO_x as well as fresh water consumption in the raw material production phase were calculated. The rest of the life cycles phases were excluded for these parameters for two reasons. Firstly, the main difference is found in the material production phase while other life-cycle phases will show very little difference between the materials evaluated. Secondly, finding values of the emissions in other phases would be very time consuming considering the small variations and limited data available. It would probably require an in-depth study on its own to assess the differences in all life-cycle phases, something which is not feasible within the given time frame.

The local environmental impact of the additive manufacturing process was evaluated as well. Available literature were studied to assess the local impact FDM-machines and the materials used can have on the work environment. This includes issues like emission of hazardous particles while printing and emissions of micro plastics.

The values calculated in the sustainability assessment provides an approximate comparison between the sustainability of the three materials. The values should not, however, be interpreted as indicators of the actual environmental impact in absolute numbers. They are only valid as a comparison between the materials analysed in this study using the same method.

5.1.1 Product Life Cycle

To evaluate the energy consumption and CO_2-emissions, the whole life cycle of the component was included. This includes the processes from production of the raw material all the way to end-of-life treatment. Hence, a life cycle model of the component was defined as shown in Figure 5.1. The figure illustrates the life-cycles of all three materials included in the assessment. A description of each step of the cycle is given in Table 5.1.

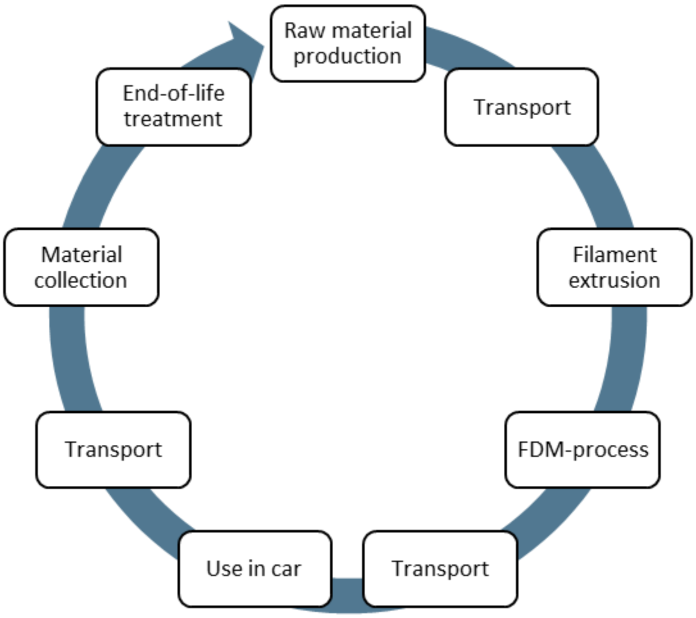


Figure 5.1: Life cycle used to calculate environmental impact of the component.

Table 5.1: Processes for which environmental impacts were calculated.

Process	**Description**
Raw material production	The process of producing the plastic granulates from raw material. Including growing the crops for bio-based materials.
Raw material transport	Transport of the plastic granulates to filament extrusion site.
Filament extrusion	Process of melting the granulates and extruding the plastic into FDM-filament.
FDM-machine process	The process of manufacturing the component in a FDM-printer.
Transport of finished product	Transport of finished product to car assembly site.
Usage in car	Usage of the component in a hybrid car during an assumed 15 years lifetime.
Material collection	Collection of material to allow for end of life treatment.
Material recycling	Mechanical recycling of the material.
Material incineration	Incineration of the material not collected for recycling.

5.1.2 Environmental Impact Indicators

When making a full scale life cycle assessment (LCA), one typically gathers data on the emissions of all hazardous substances throughout the life cycle. Making such a thorough assessment would be too time consuming considering the time frame of this thesis. Three of the environmental impact indicators considered most important was therefore selected to be used in the analysis. The first indicator is the CO_2-equvivalent emissions. This is a measurement of the products effect on climate change as result of greenhouse gas emissions. The amount of greenhouse gasses produced is recalculated to an equivalent amount of CO_2 which makes it easier to compare between different life cycles.

The second indicator is how much nitrogen oxides (NO_x) and sulphur oxides (SO_x) emissions that are created in the production processes. Emissions of NO_x into the atmosphere is one of the main reasons to poor air quality in cities today. SO_x contributes to the acidification of the environment which is one of the most critical global environmental concerns. The third indicator is the fresh water consumption which is an important factor to consider when assessing the growth of crops for production of bio-based polymers. Fresh water is a scarce resource in many parts of the world, especially in some areas where crops for bio-plastic production are often grown.

5.1.3 Calculations of Environmental Impact

The energy consumption and CO_2-emissions were calculated for each phase of the life cycle. This made it possible to evaluate how the impact differs between materials in different processes. The calculations done are based on the method used in Cambridge Engineering Selector database (CES) supplied by Granta Design [47]. A complete description of all calculations done is included in Appendix G.

Parameters used in the calculations were gathered from several sources. The main source of material and production process parameters was the CES database [47]. When required figures were not available in CES, data were drawn from related literature and research in the field. All parameters used, including information sources, are listed in Appendix F.

All environmental impacts due to transport and usage in car were approximated. Standard values of energy consumption and emission levels for passenger cars and trucks were used. The values were taken from CES [47] and from the Euro 6 emission regulation prescribing allowed emission levels for vehicles [48]. The distance travelled by a car each year was based on the yearly average car driving distance in Sweden, which was 12240 km in 2016 [49].

To get values on the energy consumption of an industrial FDM-machine, values were adopted from a study measuring the energy consumption of different AM-processes [50]. In the study, the energy consumption of a FDM-machine was measured for 18 different build orientations of the same component. By taking the mean value of these energy consumptions it was possible approximate the energy consumption to 305 MJ/kg material. Since different plastic materials have similar energy demand for processing in FDM-machines [51] it is assumed that all materials in this evaluation have the same specific energy demand. It was assumed that all materials evaluated would be recycled to 10 % after the usage phase. The other 90 % of material were assumed to be incinerated for energy recovery.

To calculate the CO_2-emissions due to energy production the average grid energy mix of the OECD (Organization for Economic Co-operation and Development) countries was used. On average, the CO_2 produced was 404 gCO_2/kWh in 2015 [52]. For the processes related to recycling, the energy consumed per kg material was assumed to be the same for all materials evaluated. The energy saving as a result of recycling is however different since the raw material production of the materials differ.

When using environmental impact data for calculations it is important to consider the uncertainty of the data. Even if measured data is available, which is not always the case in this study, the uncertainty is large. According to the database provider, CES, one can expect a standard deviation of, at best, 10 %. This implies that for drawing any statistically significant conclusions a difference in a comparison must not be smaller than 20 %.

5.2 Result

From the sustainability assessment it was evident that around 75 % of the total energy consumption and CO_2-emissions was from the car usage phase. This is illustrated in Figure 5.2. To enable a more detailed comparison between the three materials, the usage phase is excluded in Figure 5.3 below. The full results and all detailed values are presented in Appendix F.

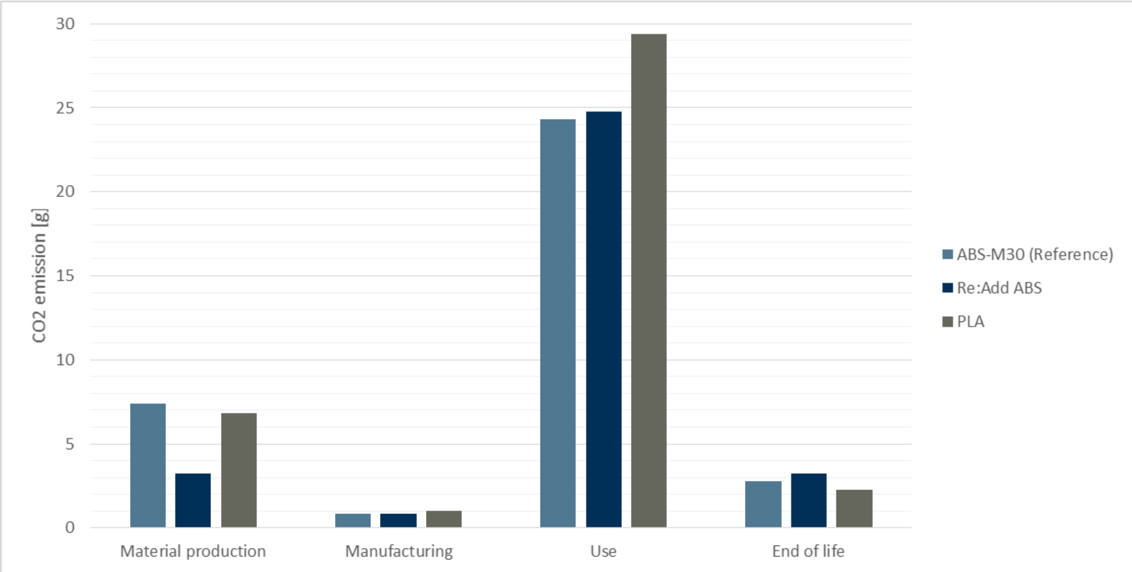


Figure 5.2: CO2-emission from each life-cycle phase for each of the three materials evaluated.

Figure 5.3 shows the CO_2-emissions for each life-cycle phase and material, with the usage phase excluded. Among these phases, the material production phase is clearly the one with largest environmental impact. When looking at the material production phase it is clear that the recycled content of the Re:Add ABS lowers the impact for this phase. The recycled amount is also the explanation for the higher impact for Re:Add ABS in the end-of-life phase. A larger energy saving can be achieved by recycling a virgin material. Since the reference and PLA materials have higher impact during production, more is also gained by reducing the need to produce new material, which is done by recycling. In the manufacturing phase the difference is small but the PLA is performing slightly worse than the other, due to the higher density.

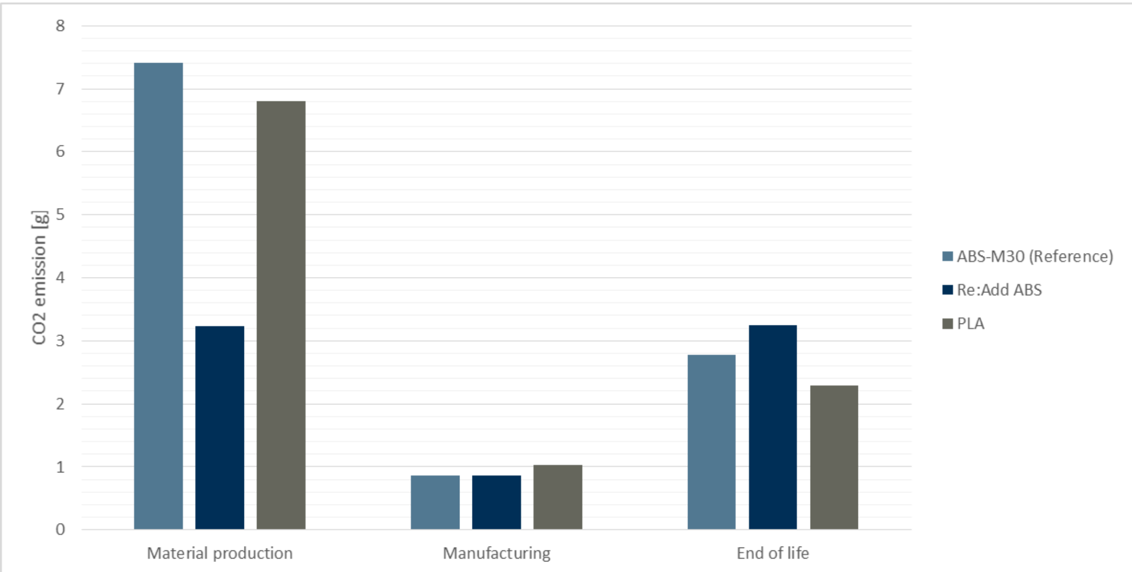


Figure 5.3: CO2-emissions for materials in each life-cycle, with the usage phase excluded.

The total CO_2 impact throughout all phases, including car usage, is summarised in Figure 5.4. As shown in the graph, PLA is the material with the largest CO_2 impact. The reason for the high value on the PLA is the higher material density. The increased component weight leads to a larger fuel consumption of the car during usage phase. This increase in fuel consumption is enough to offset the gains made by choosing a bio-based material. This is an important aspect to consider when evaluating different sustainable materials to be used in cars in general. In the calculation model used here, an increased weight of the component by 10 % would be enough to fully offset the benefits also from the recycled ABS. It is therefore important that recycled materials used have mechanical properties close to that of the corresponding virgin material. Lower mechanical properties could otherwise require a weight increase that could lead to a larger total impact when assessing the whole life cycle.

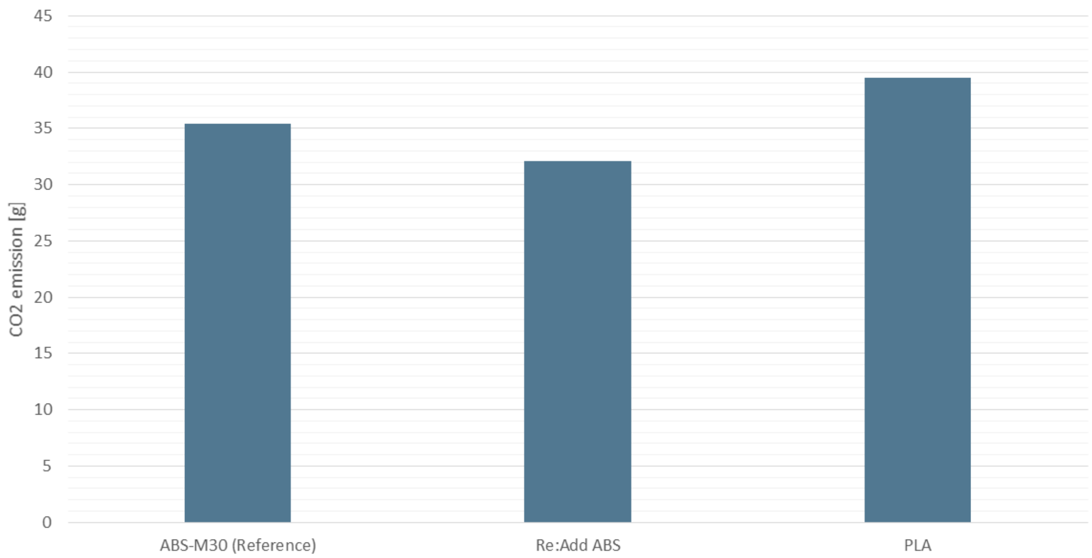


Figure 5.4: Total CO2-emission of each of the three materials including all life-cycle phases.

Comparing the total CO_2-emissions of Re:Add ABS and the reference ABS a 9 % reduced impact is shown for the Re:Add ABS. This is not, however, enough to prove a statistically significant difference. To show a more distinctive difference the usage phase was once again excluded, as shown in Figure 5.5. By doing so, a 33 % reduction of emissions is shown when comparing the reference to the Re:Add ABS. Since the usage phase for these two materials differ only by 1.8 %, this comparison is still believed to be valid.

Looking at the total CO_2-emissions of the PLA it is 12 % higher than reference, which is not a statistically significant result either. It does, however, provide a good indication of the impact of the PLA material. And when comparing Re:Add ABS and PLA to each other, the difference is 37 %, in favour for the Re:Add ABS, which clearly is a significant result.

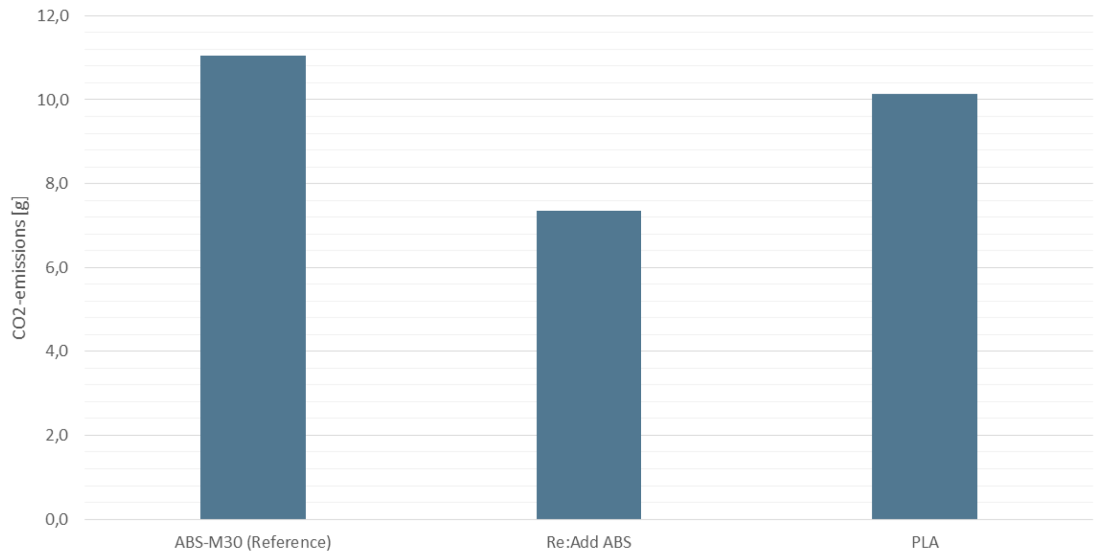


Figure 5.5: CO2-emission for each material with the usage phase excluded.

When looking at the fresh water consumption during material production, a large difference is shown, see Figure 5.6. As indicated by the figure, huge amount of fresh water is used while growing the crops for bio-polymer production. A much smaller amount is used for plastics manufactured from fossil resources. An even smaller amount is needed for the recycled ABS where the only additional water consumption process is the cleaning during recycling.

Figure 5.6: Results from calculation of fresh water consumption during material production phase.

Figure 5.7 and Figure 5.8 shows the levels of NO_x and SO_x respectively created during material production. The emissions from the virgin reference material are substantially larger than the other two materials. The Re:Add ABS has the lowest emissions, 95 % lower than the reference and 65 % lower than the PLA. The precentral difference is the same for both NO_x and SO_x- emissions even if the absolute value measured in grams differ.

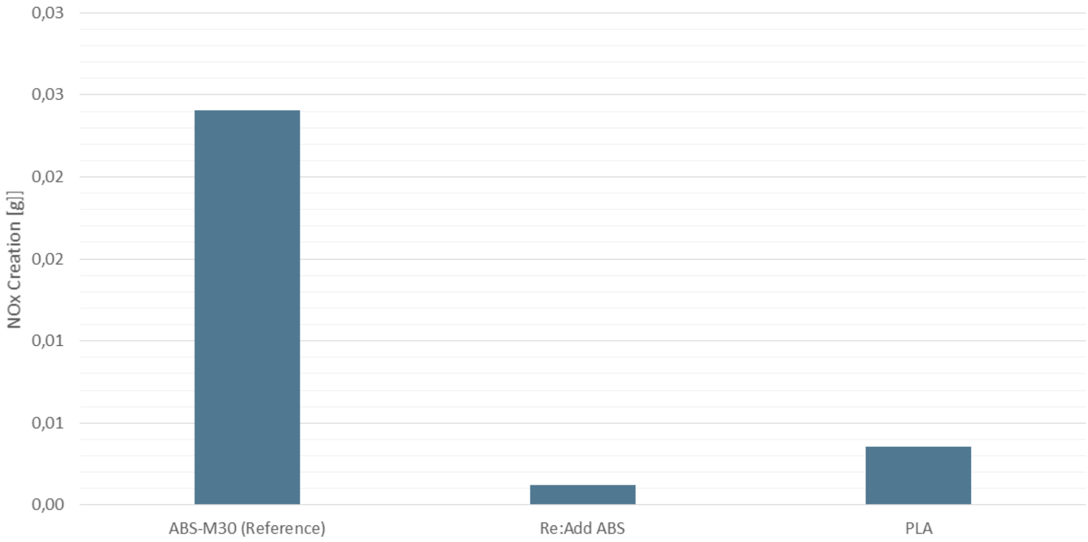


Figure 5.7: Emission of NOx from material production for each of the three materials evaluated.

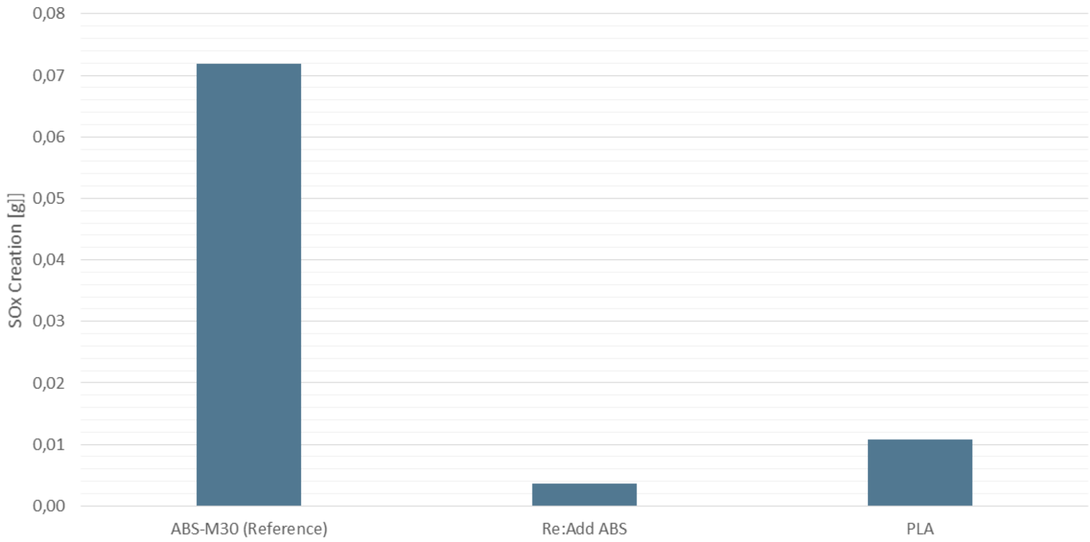


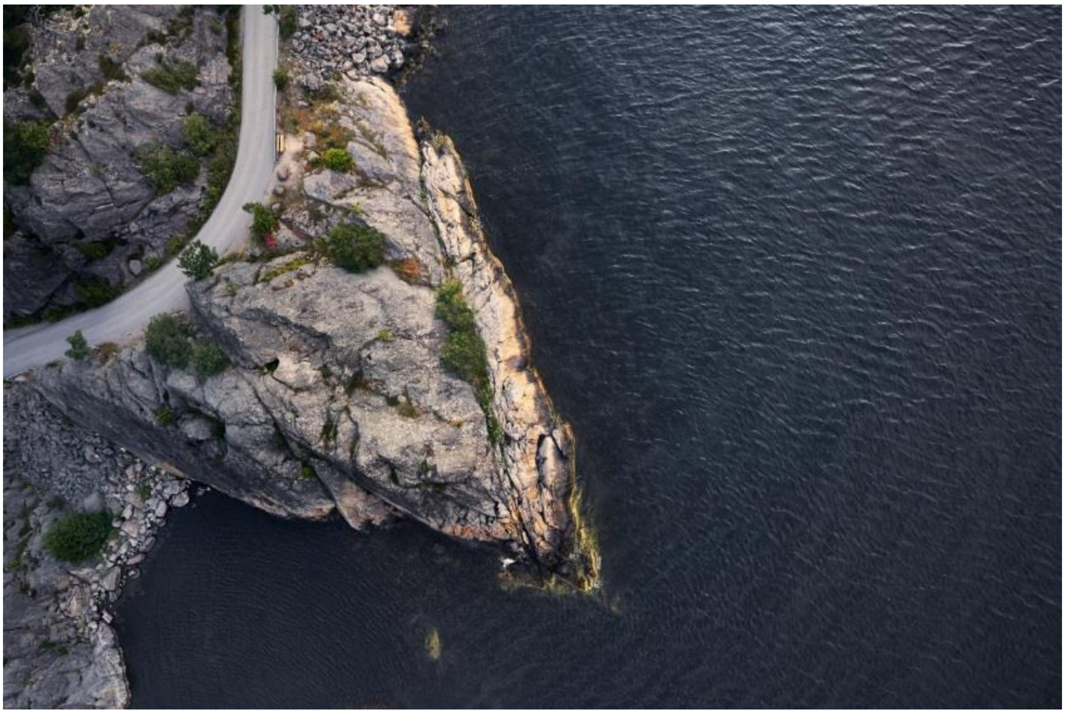
Figure 5.8: Emission of SOx from material production for each of the three materials evaluated.

When it comes to the working environment around AM-machines, recent research has suggested that hazardous emissions can be released when processing plastics with AM. In one study [53], the emissions from a FDM-machine was measured while printing an ABS and two types of PLA plastics. The results showed a large concentration increase of potentially hazardous nanoparticles while printing two of the three plastic types. Also, increased levels of carcinogenic particles were measured. Based on these results, the researchers concluded that more investigation into the potential harmfulness of processing plastics in FDM-machines is needed. Even though this subject is not covered in detail in this work, it is an important aspect to consider while implementing production with FDM-technology.

In conclusion, the sustainability showed a significant lower environmental footprint of using recycled plastic filament instead of virgin alternatives. Also for the bio-based alternative a significantly reduced impact was seen with regards to most aspects. However, the higher density of the bio-based PLA, resulting in a larger fuel consumption of the car, did offset these benefits making the PLA the least desirable material from a sustainability perspective. In addition, the fresh water consumption was drastically larger for the PLA. The assessment of NO_x and SO_x-emissions also showed a drastically lower impact from the recycled ABS compared to reference. The PLA also performed significantly better than reference but not as good as the Re:Add ABS.

Relating the different impact indicators to each other is hard and inevitably includes several assumption and simplifications. In a full scale LCA all factors would be compared with a common parameter making comparisons easier. The study done here, however, provide enough information to conclude that recycled ABS is the most environmental friendly alternative for the application investigated, with regards to the aspects evaluated. Especially considering that all assessment point to recycled material as the best alternative. This result support the decision of selecting Re:Add ABS. A more sustainable material gives a strengthened competitive position compared to the reference, especially considering that all assessment point to recycled material as the best alternative.

In this assessment, bio-based plastics and recycled plastics have been regarded as two possible way of reducing environmental impact. It is worth noting that a combination of these two alternatives might also be possible, at least in the future. The best alternative would, of course, be to produce a plastic material from bio-sources and then recycling it after usage. The possibilities for high performing components being produced in such material today is small but ongoing development is likely to push towards this type of fully closed, bio-based, material loops.

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6 Prototype

Re:Add ABS was considered the most suitable material for manufacturing of the Integration Unit. In order to test the material on the actual component a prototype was printed. This allowed for some function testing and provided a physical product that could be assessed by project stakeholders in detail.

6.1 Prototype Manufacturing

The component was manufactured in a Zyyx+ printer which is the same machine used to manufacture the test specimen for the material tests. The printing settings used to print the prototype were the ones presented in Section 4.3.1. The component was printed in the direction shown in Figure 6.1, with the circular shapes facing upwards. The chosen direction was believed to be the most appropriate considering the material test result and component geometry. Moreover, the used direction generated least support material resulting in shorter printing time.

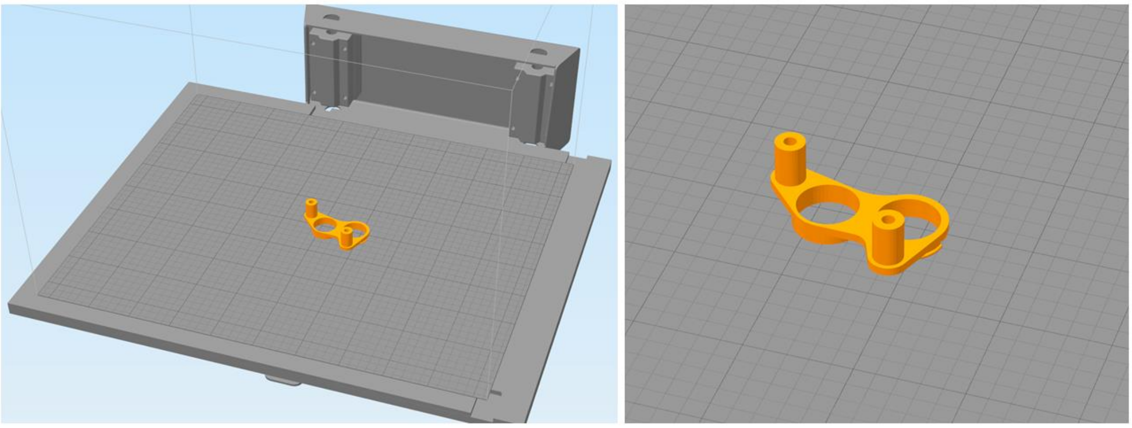


Figure 6.1: The Integration Unit prototype shown in Simplify 3D.

The component was printed in original scale and in a version scaled up to 150 %. The prototype did not undergo any surface treatment except some light grinding to remove adherent support material. The geometry could be printed without complications, however, print settings could potentially be further tuned to achieve a higher surface quality. The prototype is seen in Figure 6.2. A virtual model of the component is shown in Figure 6.3 where it is connected to the hoses as intended.

Figure 6.2: Integration Unit prototype printed in Re:Add ABS.

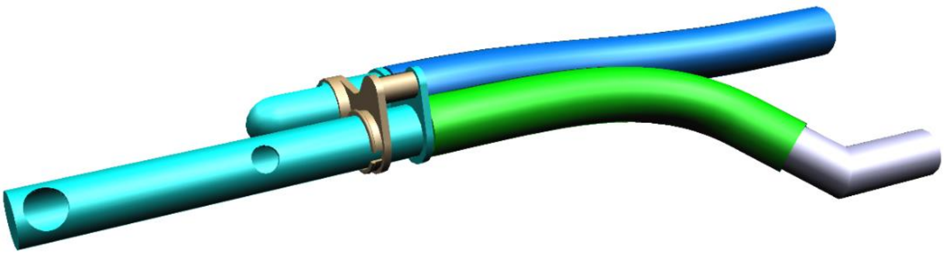


Figure 6.3: CAD model showing the assembled Integration Unit.

6.2 Cost Calculation

The cost allocation for products produced in AM differ from more traditional manufacturing techniques since there are additional cost parameters to consider. Based on a cost model designed for FDM-printing [54] a custom cost model for the specific component was developed. The model was used to calculate the unit price as well as comparing the selected concept to the reference ABS material. The complete cost calcualtion can be found in Appendix E and based on a production volume of 50 units.

6.2.1 Method

There are four cost factors to consider when using AM: processing, equipment, material and post-processing [54]. Post-processing costs were excluded to limit the scope of the analysis, however they are relevant to considered for further development. Based on the cost model proposed by Mello et al. [54] and the decision to exclude post processing job a new cost model was developed seen in Equation 7.1. The equation include a new cost factor, energy cost. Previous a part of the other factors it was broken out to visualise how energy consumption affect the total cost. The parameters in the model are further described in the sections below and all nomenclatures are explained in Table 6.1.

$$C_{total} = C_{processing} + C_{equipment} + C_{material} + C_{energy} \quad (7.1)$$

Table 6.1 Nomenclature for the cost model

C_{energy}	Energy cost [SEK]
$C_{equipment}$	Equipment cost [SEK]
C_{labour}	Total labour cost per [SEK]
$C_{material}$	Total material cost [SEK]
$C_{processing}$	Processing cost [SEK]
C_{total}	Total prototype cost [SEK]
E_{build}	Energy consumed during build [J]
P_{energy}	Energy price [SEK/J]
P_{labour}	Labour cost [SEK/h]
$P_{machine}$	Printer price [SEK/h]
$P_{material}$	Material price [SEK/kg]
$S_{operator}$	Operator salary [SEK/h]
T_{build}	Build time of one unit [h]
$T_{processing}$	Processing time per unit [h]
$W_{material}$	Weight of material per unit [kg]
$W_{support}$	Weight of support material per unit [kg]
W_{unit}	Unit weight [kg]
W_{waste}	Weight of waste material per unit [kg]

Examples of processing costs are software licenses, designer processing time and computer costs. These indirect costs can be seen as a part of the development phase, therefore these cost factors are excluded from the cost calculation. However, the machine operator charge for preparing the component for printing, which is accounted for. The work includes selecting proper printing settings and conversion of the CAD-model to the proper file format. In addition to this, the labour time associated with loading and unloading the printer is included. Thus, preparation, loading and unloading were covered under processing cost, shown in Equation 7.2. The labour cost at 350 SEK/h was attained from the internal invoicing system used by the AM-Centre at Volvo Cars. The time allocated to processing operations at the AM-Centre is 30 min. Since each model only has to be processed once, the processing time is the same for one unit as multiple ones.

$$C_{processing} = S_{operator} \times T_{processing} \quad (7.2)$$

Another processing cost is electricity consumed during the build. The energy consumption of a FDM-machine was, as described in Section 5.1.3, approximated to 305 MJ/kg material. The energy price was estimated to 0.8 SEK per kWh. The building time for one unit was acquired from the processing software Simplify 3D, which was 12 minutes. The total energy cost is given by Equation 7.3.

$$C_{energy} = E_{build} \times W_{unit} \times P_{energy} \quad (7.3)$$

The total material cost, considers both filament, support and waste material costs. For FDM-printers a waste percentage of 5 % is given in the material database CES [47]. The support material utilisation was calculated to 29 % based on the model and print settings in Simplify 3D. Due to the early development phase of Re:Add ABS the supplier Add:North had no possibility to share the market price at this point. However, ABS is slightly cheaper than virgin ABS, but also more challenging to process. Therefore, Add:North believe the market price will be similar to the virgin ABS. Based on the given information, the price for the Re:Add ABS was estimated to be 5 % larger than the reference ABS, to ensure the material price is not understated. The price for the reference ABS material was taken from an order made by Volvo Cars AM-Centre where 2.4 kg was purchased. The prices of the Re:Add ABS and the ABS reference were therefore 742 SEK/kg and 707 SEK/kg respectively. Due to the low volume, no volume discount were included at this point. However, if larger volumes are to be obtained an improvement of the raw material price can be expected. The total material cost is calculated according to Equation 7.5.

$$C_{material} = \left(W_{material} + W_{waste} + W_{support}\right) \times P_{material} \quad (7.5)$$

6.2.2 Result

The cost allocation divided on the four categories material, processing, energy and equipment is shown in Figure 6.4. Per unit, processing cost was 3.5 SEK, energy cost 0.1 SEK, equipment cost 6.6 SEK, and material cost at 1.8 SEK. Hence, the total cost of the component was 12 SEK. The equipment cost was found to be the largest cost factor constituting 55 % of the total cost while processing stood for 29 %. Choice of material has less impact constituting 15 % of the total cost. The energy consumption was found to be close to negligible on 1 %. The result showed that the total cost is less sensitive to an increased material cost compared to printer related costs. A change in print time would therefore have a great impact on the total cost. It is, for that reason, important to consider print parameters and print direction not only from a quality perspective but also from a cost perspective.

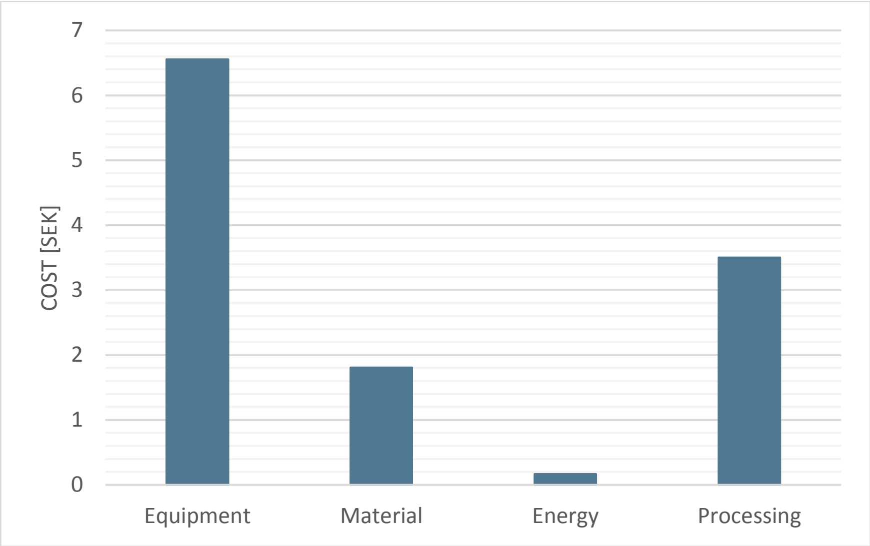
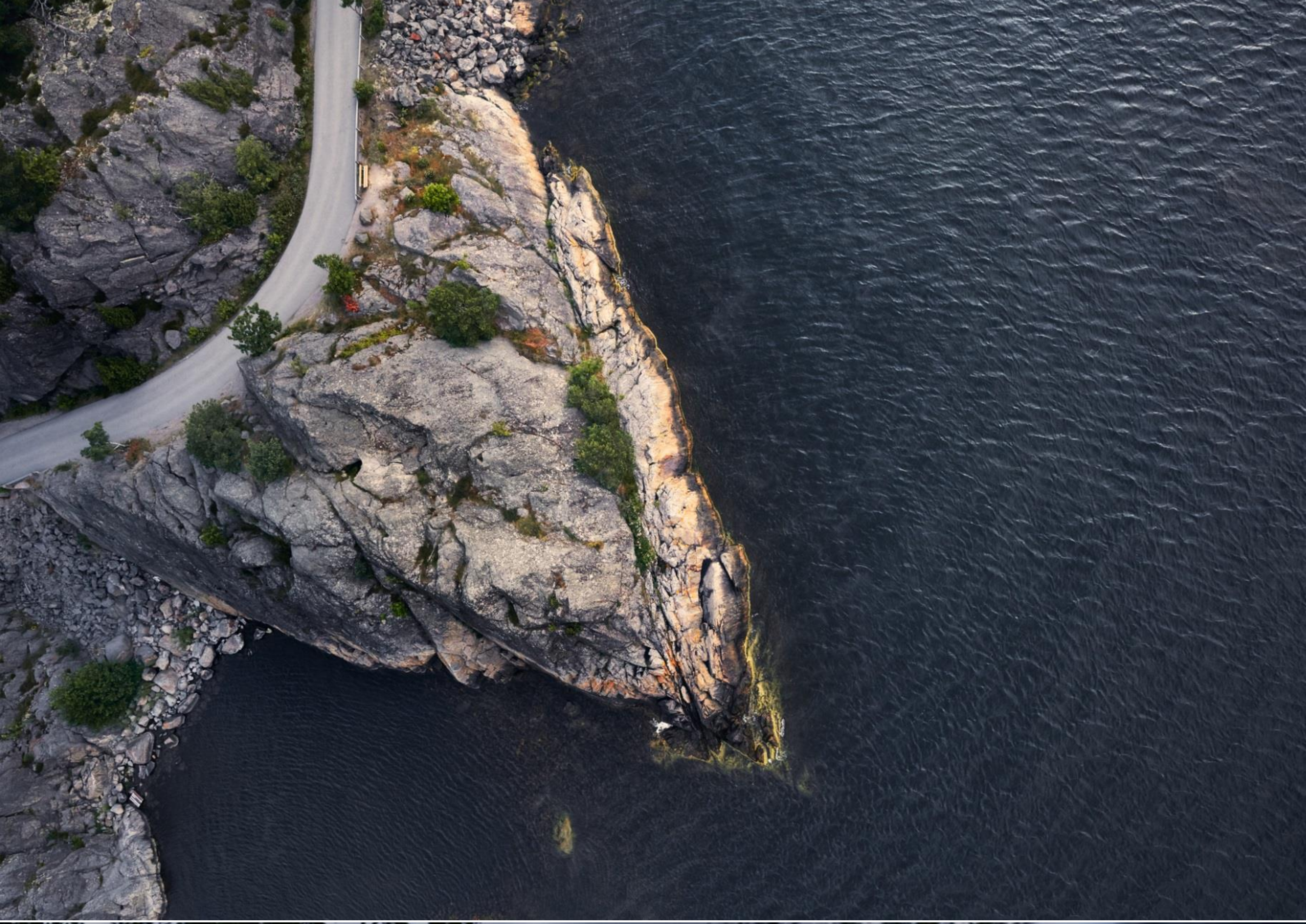


Figure 6.4: Cost allocation for the Integration Unit in Re:Add ABS.

Compared to the reference the Integration Unit in Re:Add ABS had close to identical total cost. Since ABS is used in both set ups the same print programme was used, leading to the similar result. The difference between the reference and the prototype component is the slightly higher material price for the Re:Add ABS. The total cost for printing 50 units is seen in **Error! Reference source not found.**.

Table 6.2: Cost models for the Integration Unit and the reference in virgin ABS.

Unit	**Unit production cost**	**Total production cost**
Integration Unit	12.0 SEK	602 SEK
Reference	11.9 SEK	595 SEK



7 Conclusion and Recommendations

Based on the findings presented in this report, a conclusion and recommendations are presented in this chapter. By answering the three research questions stated in the beginning, all results are combined and recommendations regarding further work and direction for Volvo Cars are presented. The questions are answered separately in the three sections below. Finally, the recommendations are summarised in shorter form in the last section.

7.1 Sustainable Plastics for FDM-Technology

What is realistic to achieve with FDM-technology in sustainable plastics?

Since most industrial FDM-machines are locked to a few specific materials, the freedom to try new materials is limited. None of the large manufacturers are offering any recycled plastic materials today, and the only available bio-based material is the PLA with highly limited thermal properties. There are, however, ways around these problems and some suppliers are offering solutions to alter machines to enable usage of any filament material. At the moment, this would be the only way of using new types of sustainable plastics in most industrial quality FDM-machines.

The results from the material test highlight the novelty of the AM technology where the knowledge of process parameters are far behind more mature manufacturing. Plastics have small processing intervals were the performance is optimised and are sensitive to modifications of process parameters. Hence, more in depth studies are needed to identify the ideal settings for new materials to be used in the future. Especially if one intends to use new types of materials in machines not officially supporting these types of plastics.

Based on the combined information gathered in this work, it can also be concluded that AM is still not, by any means, close to competing with traditional manufacturing technologies in large volumes. What this work shows, however, is that for parts and prototypes being manufactured with AM already today, a change to a more sustainable material alternative might very well be possible.

7.2 Properties of Sustainable Plastics

How does the properties of sustainable plastic materials compare to virgin plastics when used in FDM-machines?

The sustainable plastic alternatives available on the market for FDM-machines is still very limited. This is especially true for the large manufacturers. There are, however, several small firms offering different types of sustainable plastic material, also in Sweden. For a company willing to be an early adapter of recycled and bio-based plastics for low volume production, the possibilities are present.

From the material evaluation it was concluded that the bio-based materials available still are too far behind virgin and recycled materials regarding thermal properties. Also the recycled PETG tested showed inferior properties compared to virgin ABS, and was therefore insufficient for the case study component evaluated here. Development of more advanced bio-based materials for AM is undergoing and one example of this is the EU-financed Barbara project developing bio-based plastics for FDM machines to be used in interior car components. Due to the planetary resource limitations both bio-based and recycled materials are believed to be a part of a future fully sustainable solution, even if bio-based plastic filaments are not yet meeting the tough requirements for car applications.

From the testing of mechanical material properties it can be concluded that some of the recycled ABS materials have potential to work for a car interior component. The Re:Add ABS material, consisting of 95 % recycled content, performed equally well as the virgin reference ABS. The variation in properties is larger for recycled material but when evaluating average results, no significant lowering of properties can be seen for recycled plastic filaments. The larger variation do lead to a need for slightly larger safety margins. But since the variation increase is low, a component with added safety margins to compensate this would still perform better from a sustainability perspective.

It should also be noted that not all necessary verifying tests for new materials have been conducted in this case study. Additional test looking at low temperature performance, flammability and long term ageing are some examples of test needed for further understand these materials. Also, the variation in recycled material quality between production batches must be further assessed to better understand the instability in recycled material properties.

In addition to this, a better understanding for how different degrees of recycled content affect material properties is vital to establish. Recycled plastic materials deteriorate and get less durable for each recycling cycle, which create a trade-off between recycled content and durability. Thus, additional testing is needed to identify the ideal levels of recycled content depending on application.

7.3 Business Case, Environmental Impact and Implementation

Is it possible to improve profitability and decrease environmental impact by combining AM and sustainable plastics at Volvo Cars?

From the sustainability analysis it was concluded that a change from virgin plastic filament to a recycled alternative would lead to a reduction of CO_2-emissions by about 9 % during the car lifetime, assuming 10 % of the material is recycled after usage. Also the NO_x and SO_x-emissions from the recycled material is significantly lower compared to the reference.

Looking at the bio-based alternative it is harder to draw any general conclusions. The CO_2-emissions are lower for the material production phase but the higher density adds weight to the component which offsets the savings done by increasing the car fuel consumption. In other words, the car weight is still the dominating factor in order to reduce CO_2-emissions. Changing to other types of materials is important but cannot feasibly be done at the cost of significantly increased component weight. Also, the large demand on fresh water for growing crops is a problem that need to be considered when choosing bio-based plastic materials.

The cost calculation showed that equipment cost was the largest cost factor, standing for 55 % of the total cost. Compared to the reference, Re:Add ABS is a competitive alternative with only a marginally higher material price than the reference ABS material. However, the Re:Add ABS is not yet available on the market which is why the price is still somewhat uncertain. The material price for the Re:Add ABS was estimated and in reality the price could just as likely be lower than for the virgin ABS.

Based on the results regarding material properties and cost compared to virgin material used today, a relatively large scale introduction of recycled materials for prototypes would be possible. AM is believed to grow further in the coming years, the choice of material for AM-machines will have an even larger impact on the total Volvo Car environmental footprint. Assuming a reliable production process can be achieved it should be possible to use recycled material on a large variety of internal prototypes and low volume components. One way of doing this is by introducing an internal recycling system. Prototypes could then be collected after usage and in collaboration with suppliers recycled to produce new filament. There are already companies offering material recycling services, and a dialogue with a Swedish filament producer has already been held where the potential for this kind of collaboration has been discussed. One major benefit with such a closed-loop recycling system is that full overview of the material flows is possible. The uncertainty regarding the material quality in the loop can thereby be reduced. A recycling system would be one step in the right direction towards a more circular organisation and would also show on Volvo Cars commitment to the sustainability goal.

The component selected for this case study was a B-surface, a decision made due to the strict design requirements on visual components not realistic to fulfil with the FDM-technology tested here. However, one can argue that visual surfaces in sustainable materials add customer value. Even though AM is not sufficient for A-surfaces with today's standards, other manufacturing technologies might be better suited. Such an implementation could benefit Volvo's sustainability recognition by using the visual components made in sustainable plastics for marketing purposes. Worth noting is also that the materials used in FDM-filaments are more or less the same as the ones used for injection moulding. FDM could therefore be a way of evaluating new types of material in a fast and cost-efficient manner before scaling up to larger scale production with injection moulding.

The desire to work toward more sustainable plastic materials will constantly be opposed by doubt related to the uncertainties with new materials and the confidence in established ones. The sustainable material market has shown to be under upturn, and it is important as a company to be alert once new suitable and more sustainable solution become available. When it comes to recycled filament for AM, it appears to be ready for implementation in small scale production and prototyping. Regarding bio-based materials, more research and development is needed before viable applications for car components are available. This research is, however, very much being done and within a couple of years it is likely that these types of materials are available.

7.4 Recommendations

Based on what was concluded above, the final recommendations to Volvo Cars are presented in shorter form here.

- Introduce an internal recycling system for prototypes as a way of spreading and increasing knowledge of recycled material and their possibilities.
- Consider using recycled material for low volume components similar to the one evaluated in this case study.
- Further evaluate the limitations and possibilities of recycled FDM-filaments to allow for implementations in a larger variety of components in the future.
- Investigate, together with suppliers, possibilities of using filaments with different amount of recycled material as a way of adapting the material properties to the component requirements.

8 References

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Appendix A – Component Evaluation Matrix

		Component											
		Rear left uniside bracket		Air duct adapter		Dashboard air duct vent		Rear left bumper bracket		CDS bracket		Fragnance integration unit	
Ciriteria	**Weight**	**Rating**	**Weighted score**	**Rating**	**Weighted score**	**Rating**	**Weighted score**	**Rating**	**Weighted score**	**Rating**	**Weighted score**	**Rating**	**Weighted score**
Optimization potential	6%	4	0,24	2	0,12	4	0,24	4	0,24	3	0,18	1	0,06
Component size	6%	3	0,18	5	0,3	2	0,12	2	0,12	4	0,24	5	0,3
Surface finish	4%	4	0,16	4	0,16	2	0,08	4	0,16	3	0,12	5	0,2
Design complexity	10%	2	0,2	5	0,5	3	0,3	2	0,2	4	0,4	5	0,5
Limited load on component	25%	2	0,5	4	1	4	1	2	0,5	3	0,75	4	1
Temperature exposure	15%	3	0,45	4	0,6	4	0,6	3	0,45	3	0,45	4	0,6
Exposure to moisture	10%	1	0,1	2	0,2	2	0,2	1	0,1	4	0,4	2	0,2
Odour demands	10%	5	0,5	2	0,2	1	0,1	5	0,5	3	0,3	3	0,3
Production volume	14%	2	0,28	5	0,7	2	0,28	2	0,28	2	0,28	5	0,7
Total score	100%	2,61		3,78		2,92		2,55		3,12		3,86	
Rank		4		2		3		5		6		1	
Further evaluation		No		Yes		No		No		No		Yes	

Appendix B – List of FDM Materials

Name	Material	Recycled/ Biobased	Supplier
Enviro ABS	ABS	B	ThreeD materials
Recycled ABS (filament from car dashboards)	ABS	R	Refilament
rABS	ABS	R	Filamentive
RePLAy 3D 100% Recycled ABS	ABS	R	Replay 3D
Reycled ABS	ABS	R	Dimension Polymers
DURA	ABS	B	algix3D
Recycled ABS	ABS	R	Add:North 3D filament
Green-TEC series	ABS/PETG	B	Extrudr
Timberfill	PLA	B	Fillamentum
Bio-Flex F 2110	HDPE	B	FKuR
Recycled HIPS (filament from refrigerators)	HIPS	R	Refilament
bioFila® Linen	Lignin	B	TwoBears
reNETfi (100% recycled fishing nets)	Nylon	R	3r3dtm
bioPC	PC	B	Filamentive
Recycled PET	PET	R	Refilament
100% recycled PET	PET	R	B-Pet
rPETG	PETG	R	Filamentive
Carbon Fibre PET	PET	R	Filamentive
rPET	PET	R	Innofil3D
ReForm rPET	PET	R	Filaments.ca
RePETfil Recycled PET	PET	R	3r3dtm
rPETG	PETG	R	3D-fuel
ALGA	PLA	B	algix3D
Entwind (Hemp filament)	PLA	B	3D-fuel
Buzzed (Beer filament)	PLA	B	3D-fuel
Advanced PLA	PLA	B	3D-Fuel
Woodfill (70%PLA - 30% recycled woodfibres)	PLA	B	ColorFabb
Wound up (Coffee Filament)	PLA	B	3D-fuel
Recycled PLA (filament from food packaging)	PLA	R	Refilament
EUBIO/2Life	PLA	R	EUMakers
rPLA	PLA	R	Filamentive
Wood PLA	PLA	B	Filamentive
Bio-Flex 3D Clear	PLA	B	FKuR
CFR PLA	PLA	B	Filaments.ca
WOOD flament	PLA	B	Filaments.ca
ECOMAX® HT High Temperature PLA	PLA	B	3dxtech
3RPLA	PLA	R	3r3dtm
PLA+ Granito Marmol	PLA	B	3r3dtm
PLA + Sand from Beach	PLA	B	3r3dtm
PLA + GRAPHENE filament	PLA	B	3r3dtm
GRAFYLON® 3D	PLA	B	FiloAlfa
Graphene Enhanced 3D filament	PLA	B	Haydale
Biome3D	PLA	B	3Dom USA
Add:pro HT-PLA	PLA	B	Add:North 3D filament
Starflax 3D	PLA	B	Nanovia
Flax	PLA	B	Extrudr
Corkfill	PLA	B	ColorFabb
Bio-Flex F 6510	PLA	B	FKuR
Bio-Flex F 7510	PLA	B	FKuR
Fibrolon 3D Natural fibers (Bamboo/Cork/Wood)	PLA	B	FKuR
Bio-Flex A 4100 CL	PP	B	FKuR
OWA	PS	R	Armor 3D filament
Repsfil PS	PS	R	3R3D Technology Materials
PVA Natural	PVA	B	Octofiber

Appendix C – Recalculation of Heat Deflection Temperature Specimen Size

The ASTM D648 standard prescribes the use of a specimen length of 127 mm, width of 12 mm and thickness of 3-13 mm. The maximum specimen size allowed in the Texas Instrument DMA Q800 is 50 mm length, 15 mm width and 7 mm thickness. To make a test with the smaller specimen valid according to the standard, the following machine parameters were calculated:

1. Force required to achieve the desired stress in the DMA specimen
2. The strain (ε) in the ASTM specimen when deflected by 0.25 mm
3. Required deflection in the DMA specimen to induce a strain equivalent to ε

The specimen sized used in the analysis had a length of 60 mm, width of 11.95 mm and a thickness of 4.45 mm. The specimen is made a bit longer than the clamping distance of 50 mm to allow easier clamping of the specimen during testing. The clamping distance of 50 mm is, however, used in the calculations.

1. Calculation of the force

$$F = \frac{2\sigma W_{DMA} T_{DMA}^2}{3L_{DMA}} = \frac{2 \cdot 0.455 \cdot 11.95 \cdot 4.45^2}{3 \cdot 50} = 1.44\ N$$

2. Calculation of the strain in ASTM specimen at 0.25 mm deflection

$$\varepsilon = \frac{6 \cdot d_{ASTM} \cdot T_{ASTM}}{L_{ASTM}^2} = \frac{6 \cdot 0.25 \cdot 13}{127^2} = 0.121\%$$

3. Calculation of DMA specimen deflection

$$d_{DMA} = \frac{\varepsilon L_{DMA}^2}{6T_{DMA}} = \frac{0.00121 \cdot 50^2}{6 \cdot 4.45} = 0.113\ mm = 113\ \mu m$$

Where

σ = Stress in the specimen
ε = Strain in the specimen
d_{ASTM} = Deflection in the ASTM specimen (0.25 mm)
d_{DMA} = Deflection in DMA specimen at ε strain
F = Force on the DMA specimen to achieve σ stress
L_{ASTM} = Length of the ASTM specimen (127 mm)
L_{DMA} = Length of the DMA specimen (50 mm)
T_{ASTM} = Thickness of the ASTM specimen (13 mm)
T_{DMA} = Thickness of the DMA specimen (4.45 mm)
W_{DMA} = Width of the DMA specimen (11.95 mm)

Appendix D – Material Tests Documentation

Material Specimen Coding

Each test specimen is provided with a unique name based on the material, build orientation and ageing as described in the table below. Each specimen is also given a serial number at the end since there are several specimens with the same properties. As an example: The first specimen of the rABS without ageing printed in X-direction is called, CX01. For the odour test the temperature and moisture parameters replaced the ageing parameters. For example, the first specimen of the rPET heated in the heating chamber and put in a water solution is named EX21. Material D was excluded early in the process, before testing started, and is therefore omitted from all results.

Material	**Code**
ABS-M30 – Stratasys (Fortus mc380)	A
ABS-M30 – Stratasys (Zyyx+)	B
rABS – Filamentive	C
Omitted	D
rPETG – Filamentive	E
Add:Pro HT-PLA - Add:North	F
Enviro ABS - ThreeD materials	G
Re:Add ABS – Add:North	H

Direction	**Code**
Longitudinal - X-direction	X
Transversal - Y-direction	Y

Ageing		**Code**
No ageing		0
Temp: 70 °C	Humidity: 2 %RH	1
Temp: 70 °C	Humidity: 55 %RH	2

Odour		**Code**
Heated: No	Water: No	0
Heated: Yes	Water: No	1
Heated: Yes	Water: Yes	2

Tensile Test Results

Tensile Test - Material A	
Machine settings	
Machine model	Zwick/Roell RetroLine
Loading rate	50 mm/min
Capacity	10 kN

Result					
Test sample	**Width [mm]**	**Thickness [mm]**	**Ultimate tensile strength [MPa]**	**Tensile modulus [MPa]**	**Elongation at break [%]**
AX01	12,99	3,58	26,10	2147	6,10
AX02	12,99	3,59	29,20	2382	5,59
AX03	13,01	3,55	26,50	2701	4,99
AX04	13,01	3,58	26,40	2145	4,95
AX05	13,01	3,58	26,50	3008	5,59
AX11	13,02	3,55	26,83	1886	4,71
AX12	12,97	3,55	26,87	2676	4,14
AX13	13,00	3,54	26,96	2518	4,94
AX14	13,00	3,60	26,01	2342	4,51
AX15	12,97	3,55	26,98	2809	5,24
AX21	12,98	3,51	28,18	2766	4,62
AX22	12,99	3,58	26,90	2841	6,02
AX23	12,99	3,59	26,48	2460	4,84
AX24	13,02	3,59	25,74	3170	5,12
AX25	12,99	3,60	26,43	2275	5,72
AY01	13,08	3,20	31,80	3429	6,15
AY02	13,12	3,20	31,20	3044	5,02
AY03	13,10	3,20	30,90	2903	5,21
AY04	13,06	3,17	31,20	3132	5,43
AY05	13,10	3,17	30,90	3043	6,32

Mean Values						
Test sample	**Ultimate tensile strength [MPa]**	**Tensile modulus [MPa]**	**Elongation at break [%]**	**Stdev UTS [MPa]**	**Stdev TM [MPa]**	**Stdev EAB**
AX0_mean	26,94	2477	5,44	1,27	374,26	0,48
AX1_mean	26,73	2446	4,71	0,40	358,59	0,42
AX2_mean	26,75	2703	5,26	0,90	347,55	0,59
AY0_mean	31,20	3110	5,63	0,37	196,18	0,58

Tensile Test - Material B

Machine settings	
Machine model	Zwick/Roell RetroLine
Loading rate	50 mm/min
Capacity	10 kN

Result

Test sample	Width [mm]	Thickness [mm]	Ultimate tensile strength [MPa]	Tensile modulus [MPa]	Elongation at break [%]
BX01					
BX02	13,02	3,98	26,60	2028	4,70
BX03	13,11	3,92	27,10	2115	3,63
BX04	12,95	3,93	27,40	2066	4,87
BX05	13,39	3,82	28,10	2334	5,94
BX11	13,15	3,96	26,70	2507	4,10
BX12	13,26	3,92	27,69	2348	5,88
BX13	13,03	3,98	25,75	2188	5,00
BX14	12,99	3,90	28,04	2292	5,06
BX15	12,99	3,97	27,21	2336	3,79
BX21	13,35	3,61	30,43	3247	3,83
BX22	13,59	3,55	32,41	3122	4,13
BX23	13,28	3,62	29,62	2727	2,74
BX24	13,49	3,68	29,66	3023	4,84
BX25	13,33	3,59	31,16	2913	4,23
BY01	13,73	3,66	40,08	3056	3,23
BY02	13,60	3,66	40,26	2994	5,30
BY03	13,74	3,66	40,06	3346	5,54
BY04	13,61	3,62	40,96	3334	3,01
BY05	13,64	3,65	40,54	3367	3,56

Mean Values

Test sample	Ultimate tensile strength [MPa]	Tensile modulus [MPa]	Elongation at break [%]	Stdev UTS [MPa]	Stdev TM [MPa]	Stdev EAB [%]
BX0_mean	27,30	2136	4,79	0,63	136,99	0,95
BX1_mean	27,08	2334	4,77	0,90	115,30	0,83
BX2_mean	30,66	3006	3,95	1,17	198,99	0,77
BY0_mean	40,38	3219	4,13	0,38	179,28	1,20

Tensile Test - Material C

Machine settings	
Machine model	Zwick/Roell RetroLine
Loading rate	50 mm/min
Capacity	10 kN

Result

Test sample	Width [mm]	Thickness [mm]	Ultimate tensile strength [MPa]	Tensile modulus [MPa]	Elongation at break [%]
CX01	13,01	3,35	36,43	2350	9,56
CX02	13,18	3,35	36,11	2079	12,76
CX03	13,36	3,13	35,74	2762	5,90
CX04	13,20	3,35	34,29	2202	10,11
CX05	13,15	3,32	37,28	2783	9,00
CX11	13,09	3,34	35,31	2478	8,01
CX12	12,99	3,33	36,42	2763	8,25
CX13	13,15	3,33	35,65	2245	11,89
CX14	13,21	3,35	35,40	1960	13,99
CX15	13,13	3,36	34,71	1611	7,43
CX21	13,37	3,33	38,55	2374	10,93
CX22	13,22	3,46	33,19	2132	6,48
CX23	13,02	3,38	34,32	2372	6,11
CX24	13,14	3,41	33,99	1510	7,73
CX25	13,02	3,42	34,44	1808	8,78
CY01	13,37	3,59	40,15	2688	6,09
CY02	13,34	3,55	39,94	2626	4,58
CY03	13,60	3,61	39,04	2597	5,14
CY04	13,47	3,68	39,32	2764	21,12
CY05	13,49	3,67	38,80	2810	19,58

Mean Values

Test sample	Ultimate tensile strength [MPa]	Tensile modulus [MPa]	Elongation at break [%]	Stdev UTS [MPa]	Stdev TM [MPa]	Stdev EAB [%]
CX0_mean	35,97	2435	9,47	1,10	322,63	2,46
CX1_mean	35,50	2211	9,91	0,62	447,36	2,87
CX2_mean	34,90	2039	8,01	2,10	375,78	1,95
CY0_mean	39,45	2697	11,30	0,58	90,13	8,30

Tensile Test - Material E

Machine settings	
Machine model	Zwick/Roell RetroLine
Loading rate	50 mm/min
Capacity	10 kN

Result

Test sample	Width [mm]	Thickness [mm]	Ultimate tensile strength [MPa]	Tensile modulus [MPa]	Elongation at break [%]
EX01	13,15	3,33	36,37	2122	7,08
EX02	13,25	3,25	35,76	2399	6,71
EX03	13,10	3,34	35,63	2087	6,60
EX04	13,07	3,32	34,70	2346	5,56
EX05	12,97	3,26	36,34	2477	7,29
EX11	13,02	3,42	34,95	3217	4,85
EX12	13,06	3,40	36,39	4048	4,59
EX13	13,09	3,47	32,00	3130	4,45
EX14	13,05	3,40	33,45	3933	5,76
EX15	13,11	3,37	36,99	3706	4,87
EX21	13,02	3,44	31,24	3273	7,12
EX22	13,11	3,38	29,72	3262	2,28
EX23	12,92	3,48	32,22	1993	8,09
EX24	12,92	3,48	33,08	1766	6,71
EX25	13,02	3,46	31,81	3533	5,97
EY01	13,47	3,38	45,72	2336	31,53
EY02	13,47	3,12	45,80	2434	2,61
EY03	13,57	3,32	43,91	2917	2,72
EY04	13,58	3,36	45,40	2258	36,17
EY05	12,80	3,36	45,04	2679	2,63

Mean Values

Test sample	Ultimate tensile strength [MPa]	Tensile modulus [MPa]	Elongation at break [%]	Stdev UTS [MPa]	Stdev TM [MPa]	Stdev EAB [%]
EX0_mean	35,76	2286	6,65	0,68	172,43	0,67
EX1_mean	34,76	3607	4,91	2,06	415,56	0,51
EX2_mean	31,62	2766	6,03	1,25	819,82	2,23
EY0_mean	45,17	2525	15,13	0,77	270,40	17,17

Tensile Test - Material G

Machine settings	
Machine model	Zwick/Roell RetroLine
Loading rate	50 mm/min
Capacity	10 kN

Result

Test sample	Width [mm]	Thickness [mm]	Ultimate tensile strength [MPa]	Tensile modulus [MPa]	Elongation at break [%]
GX01	13,13	3,40	31,36	2403	5,66
GX02	13,30	3,41	28,33	2060	7,30
GX03	13,15	3,36	31,70	2223	5,98
GX04	13,13	3,45	28,59	2097	4,41
GX05	13,14	3,41	29,11	2064	6,89
GX11	13,02	3,37	32,95	2669	9,36
GX12	13,25	3,42	32,82	2634	6,00
GX13	13,57	3,50	30,25	2063	5,45
GX14	13,11	3,47	27,75	2981	3,70
GX15	13,10	3,40	31,84	2288	6,95
GX21	13,02	3,51	29,39	2162	4,24
GX22	13,16	3,39	29,57	2142	5,80
GX23	13,20	3,22	34,10	2361	6,55
GX24	13,14	3,32	33,03	2488	5,75
GX25	13,12	3,41	29,02	3154	4,97
GY01	13,56	3,62	34,82	2763	6,55
GY02	13,50	3,66	34,23	2662	3,15
GY03	13,54	3,67	34,08	3075	5,11
GY04	13,54	3,56	34,42	3233	3,19
GY05	13,52	3,62	34,35	2965	3,77

Mean Values

Test sample	Ultimate tensile strength [MPa]	Tensile modulus [MPa]	Elongation at break [%]	Stdev UTS [MPa]	Stdev TM [MPa]	Stdev EAB [%]
GX0_mean	29,82	2170	6,05	1,59	146,37	1,13
GX1_mean	31,12	2527	6,29	2,17	356,84	2,08
GX2_mean	31,02	2461	5,46	2,36	412,99	0,88
GY0_mean	34,38	2940	4,35	0,28	231,08	1,46

Tensile Test - Material H

Machine settings	
Machine model	Zwick/Roell RetroLine
Loading rate	50 mm/min
Capacity	10 kN

Result

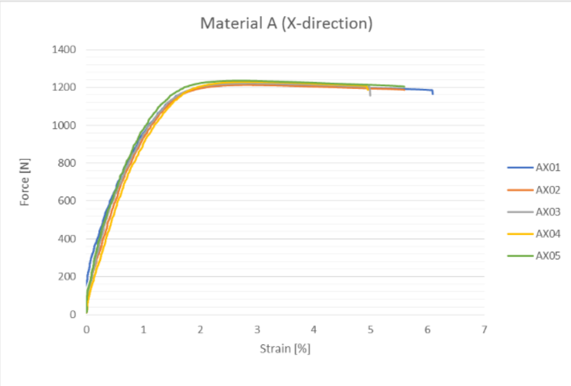
Test sample	Width [mm]	Thickness [mm]	Ultimate tensile strength [MPa]	Tensile modulus [MPa]	Elongation at break [%]
HX01	13,20	3,43	33,41	2785	6,52
HX02	13,14	3,65	28,70	2105	6,16
HX03	13,08	3,63	29,58	2286	4,38
HX04	13,18	3,57	31,00	2133	4,25
HX05	13,10	3,58	31,20	2590	4,04
HX11	13,22	3,35	37,97	3676	7,86
HX12	13,12	3,59	30,55	3095	5,81
HX13	13,13	3,59	30,66	2601	3,82
HX14	13,12	3,58	30,44	2840	4,16
HX15	13,19	3,55	31,27	3017	3,61
HX21	13,17	3,59	29,91	2696	3,51
HX22	13,01	3,60	30,34	2879	4,21
HX23	13,06	3,68	28,92	2617	3,21
HX24	13,02	3,64	29,46	2591	4,23
HX25	13,03	3,70	28,86	3095	3,84
HY01	13,53	3,65	37,95	3079	6,59
HY02	13,54	3,58	37,12	2998	4,01
HY03	13,57	3,68	36,17	3353	4,90
HY04	12,71	3,67	39,49	3943	2,07
HY05	13,54	3,65	37,33	3876	8,71

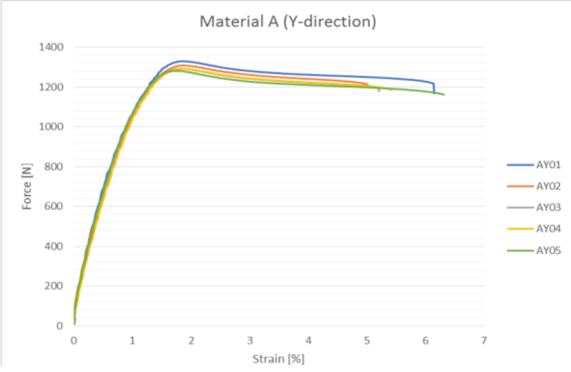
Mean Values

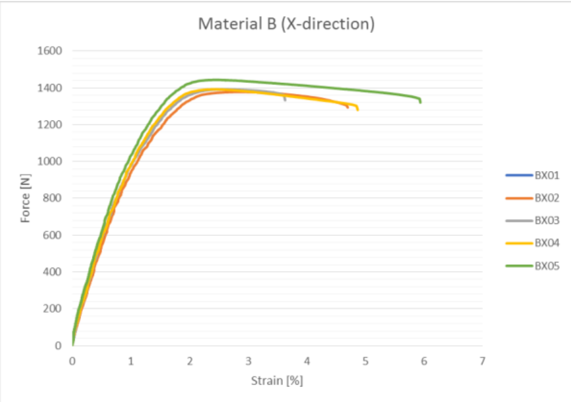
Test sample	Ultimate tensile strength [MPa]	Tensile modulus [MPa]	Elongation at break [%]	Stdev UTS [MPa]	Stdev TM [MPa]	Stdev EAB [%]
HX0_mean	30,78	2380	5,07	1,80	297,48	1,17
HX1_mean	32,18	3046	5,05	3,25	400,37	1,79
HX2_mean	29,50	2776	3,80	0,64	210,95	0,44
HY0_mean	37,61	3450	5,26	1,23	440,54	2,53

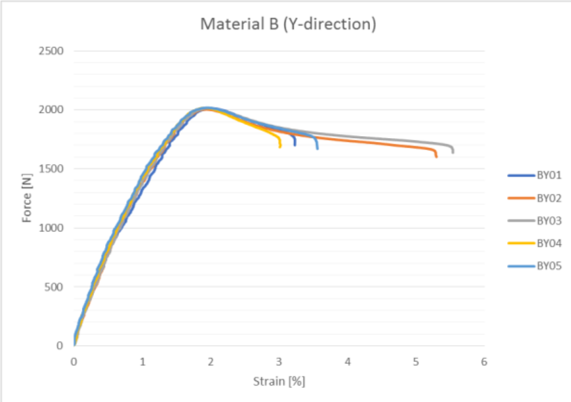
Tensile Test Result Graphs

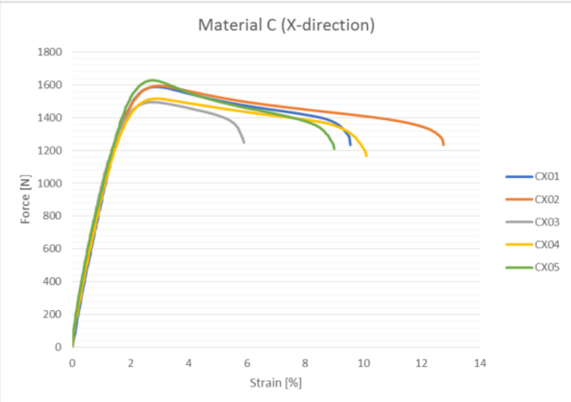
Graphs showing the result from tensile tests of all materials printed in X- and Y-direction respectively without any ageing procedure.

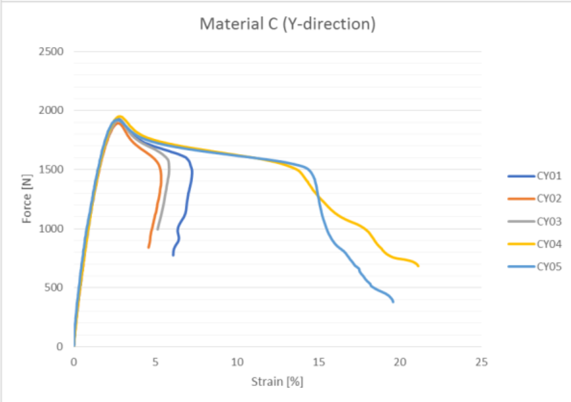


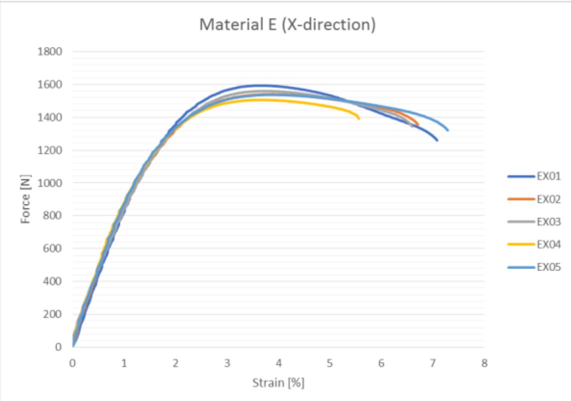


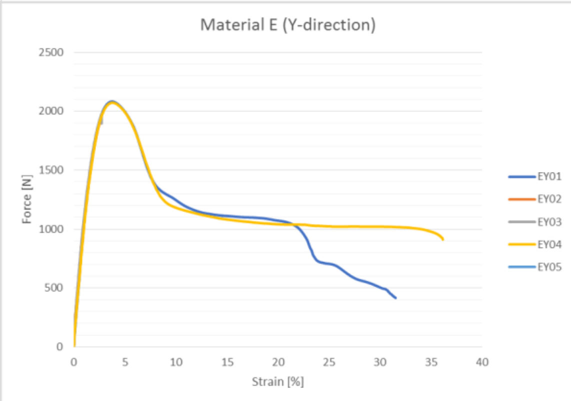


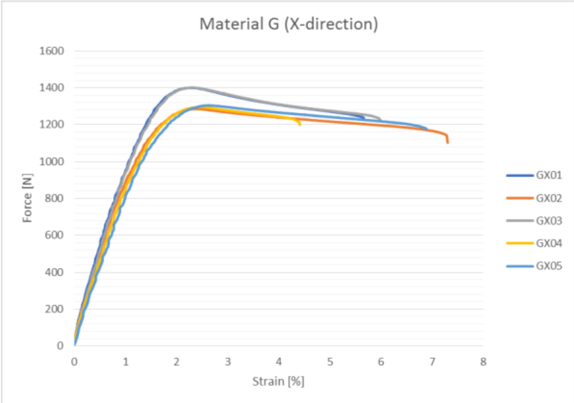


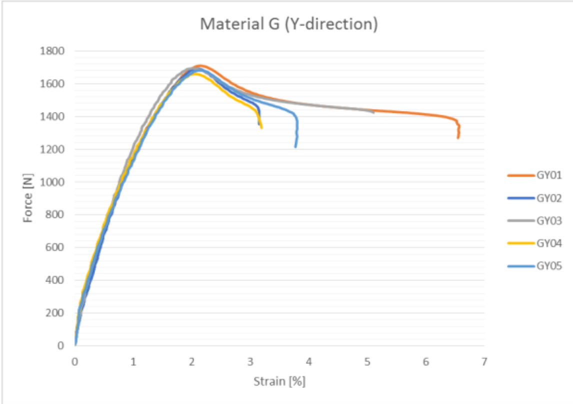


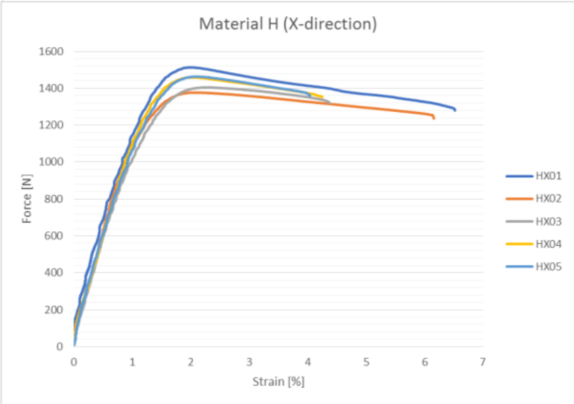


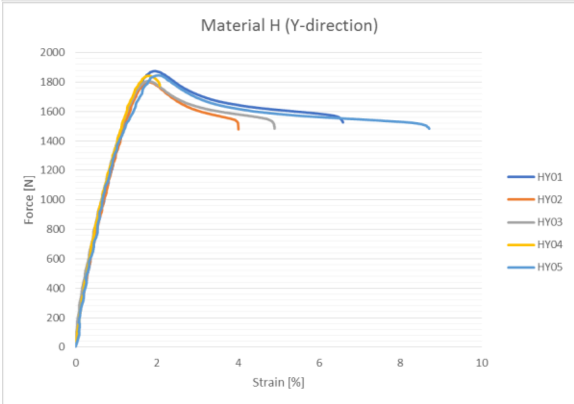





Material G (X-direction)
Force [N]
Strain [%]
0
200
400
600
800
1000
1200
1400
1600
0 1 2 3 4 5 6 7 8
GX01
GX02
GX03
GX04
GX05


Material G (Y-direction)
Force [N]
Strain [%]
0
200
400
600
800
1000
1200
1400
1600
1800
0 1 2 3 4 5 6 7
GY01
GY02
GY03
GY04
GY05


Material H (X-direction)
Force [N]
Strain [%]
0
200
400
600
800
1000
1200
1400
1600
0 1 2 3 4 5 6 7
HX01
HX02
HX03
HX04
HX05


Material H (Y-direction)
Force [N]
Strain [%]
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0 2 4 6 8 10
HY01
HY02
HY03
HY04
HY05

Heat Deflection Temperature Test

Heat Deflection Temperature Test	
Machine settings	
Machine model	Texas Instrument DMA Q800
Applied load	1.44 N
Loading rate	2 °C/min

X-direction

Test sample	HDT [°C]
AX01	105
AX02	104

Test sample	HDT [°C]
BX01	93
BX02	94

Test sample	HDT [°C]
CX01	78
CX02	77

Test sample	HDT [°C]
EX01	70
EX02	70

Test sample	HDT [°C]
FX01	54
FX02	55

Test sample	HDT [°C]
GX01	95
GX02	94

Test sample	HDT [°C]
HX01	95
HX02	95

Y-direction

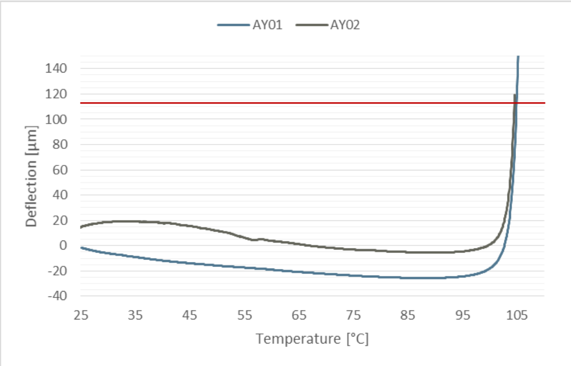
Test sample	HDT [°C]
FY01	55
FY02	55

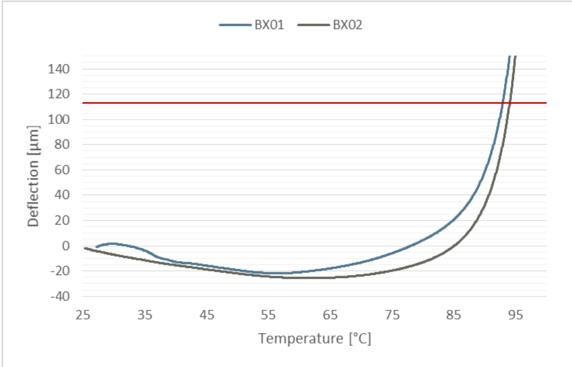
Mean Values

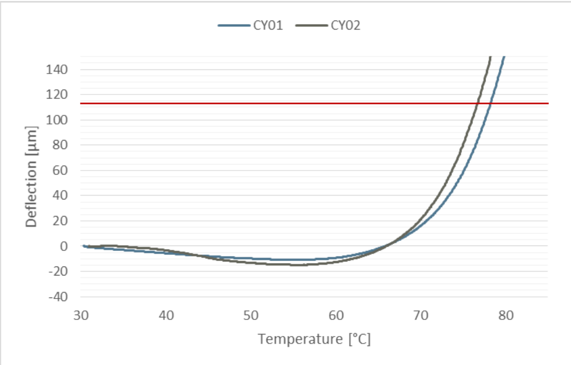
Test sample	HDT [°C]	Stdev [°C]
AX0_mean	105	0,71
BX0_mean	94	0,71
CX0_mean	78	0,71
EX0_mean	70	0,07
FX0_mean	55	0,71
GX0_mean	95	0,71
HX0_mean	95	0,07

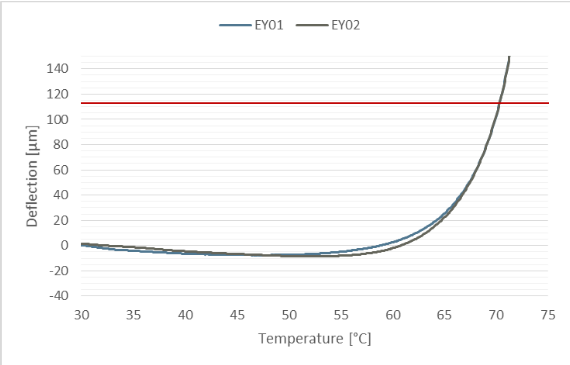
Heat Deflection Temperature Result Graphs

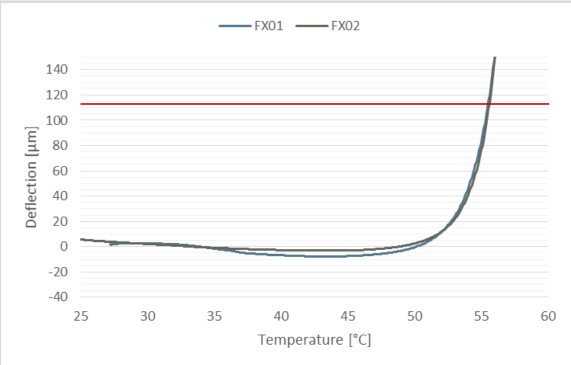
Results from HDT measurements where two specimens were measured for each material. HDT is defined as the temperature at which the deflection reaches 113 µm, marked with a red line in the graphs.

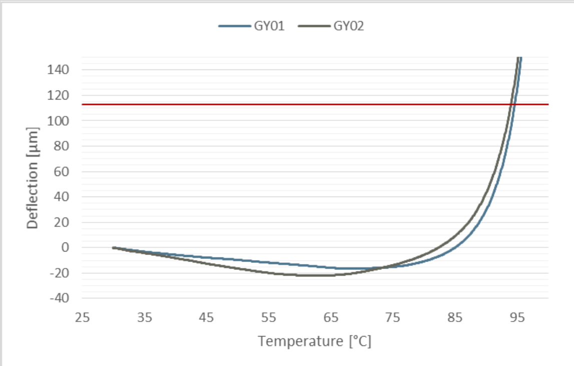


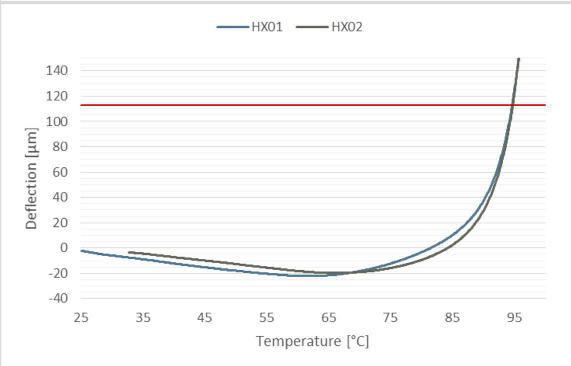












Impact Resistance Test Results

Impact resistance test						
Test conditions			**Machine settings**			
Air temperature		20 °C	Machine model	Frank		
			Impact blow	40 kpcm = 0,981 J		

Material A						
Test sample	**Width [mm]**	**Thickness [mm]**	**Absorbed energy [kpcm]**	**Absorbed energy [J]**	**J/m²**	**J/m**
AX01	11,1	6,9	6,9	0,68	8838	98,1
AX02	11,0	6,9	7,4	0,73	9564	105,2
AX03	10,9	6,9	7,4	0,73	9652	105,2
AX04	11,1	6,8	7,3	0,72	9488	105,3
AX05	11,2	6,9	6,9	0,68	8759	98,1
AY01	11,0	6,5	6,7	0,66	9193	101,1
AY02	11,0	6,5	6,8	0,67	9330	102,6
AY03	10,8	6,5	7,4	0,73	10341	111,7
AY04	11,2	6,5	7,0	0,69	9433	105,6
AY05	10,8	6,5	7,2	0,71	10062	108,7

Mean Material A						
Test sample	**Absorbed energy [J]**	**J/m²**	**J/m**	**Stdev [J]**	**Stdev [J/m²]**	**Stdev [J/m]**
AX0_mean	0,70	9260	102,4	0,03	426	3,9
AY0_mean	0,69	9672	105,9	0,03	501	4,3

Material B						
Test sample	**Width [mm]**	**Thickness [mm]**	**Absorbed energy [kpcm]**	**Absorbed energy [J]**	**J/m²**	**J/m**
BX01	9,7	7,3	9,8	0,96	13577	131,7
BX02	9,6	6,5	7,7	0,76	12105	116,2
BX03	11,0	7,2	9,7	0,95	12015	132,2
BX04	10,5	6,9	7,5	0,74	10155	106,6
BX05	9,7	7,5	8,6	0,84	11597	112,5
BY01	9,7	7,6	9,1	0,89	12109	117,5
BY02	10,1	7,0	8,2	0,80	11378	114,9
BY03	10,0	7,3	9,7	0,95	13035	130,4
BY04	10,0	7,1	7,5	0,74	10363	103,6
BY05	9,9	7,2	8,3	0,81	11423	113,1

Mean Material B						
Sample Test	**Absorbed energy [J]**	**J/m²**	**J/m**	**Stdev [J]**	**Stdev [J/m²]**	**Stdev [J/m]**
BX0_mean	0,85	11890	119,8	0,11	1225	11,6
BY0_mean	0,84	11662	115,9	0,08	989	9,6

Material C						
Sample Test	**Width [mm]**	**Thickness [mm]**	**Absorbed energy [kpcm]**	**Absorbed energy [J]**	**J/m²**	**J/m**
CX01	10,3	6,8	10,7	1,05	14987	154,4
CX02	10,9	6,8	7,9	0,77	10456	114,0
CX03	11,1	6,8	8,4	0,82	10917	121,2
CX04	10,0	6,9	8,0	0,78	11374	113,7
CX05	11,0	6,8	6,9	0,68	9049	99,5
CY01	10,4	7,0	11,3	1,11	15227	158,4
CY02	10,2	6,9	9,4	0,92	13102	133,6
CY03	10,1	6,9	11,1	1,09	15625	157,8
CY04	10,3	6,9	8,9	0,87	12285	126,5
CY05	10,4	7,0	9,0	0,88	12128	126,1

Mean Material C						
Sample Test	**Absorbed energy [J]**	**J/m²**	**J/m**	**Stdev [J]**	**Stdev [J/m²]**	**Stdev [J/m]**
CX0_mean	0,82	11357	120,6	0,14	2208	20,5
CY0_mean	0,98	13673	140,5	0,11	1648	16,3

Material E						
Sample Test	Width [mm]	Thickness [mm]	Absorbed energy [kpcm]	Absorbed energy [J]	J/m²	J/m
EX01	11,2	6,6	4,1	0,40	5441	60,9
EX02	11,2	6,7	5,5	0,54	7190	80,5
EX03	10,9	6,6	2,7	0,26	3682	40,1
EX04	11,4	6,7	3,3	0,32	4238	48,3
EX05	11,3	6,7	4,2	0,41	5442	61,5
EY01	10,2	6,5	4,5	0,44	6658	67,9
EY02	11,3	6,5	5,4	0,53	7212	81,5
EY03	10,9	6,6	2,5	0,25	3409	37,2
EY04	10,8	6,5	3,9	0,38	5450	58,9
EY05	11,0	6,6	5,7	0,56	7702	84,7

Mean Material E						
Sample Test	Absorbed energy [J]	J/m²	J/m	Stdev [J]	Stdev [J/m²]	Stdev [J/m]
EX0_mean	0,39	5199	58,3	0,10	1352	15,3
EY0_mean	0,43	6086	66,0	0,13	1716	19,2

Material G						
Sample Test	Width [mm]	Thickness [mm]	Absorbed energy [kpcm]	Absorbed energy [J]	J/m²	J/m
GX01	10,7	6,8	19,0	1,86	25617	274,1
GX02	10,7	6,9	18,6	1,82	24714	264,4
GX03	10,5	6,8	17,7	1,74	24319	255,3
GX04	9,9	7,0	17,5	1,72	24773	245,3
GX05	6,8	6,9	19,2	1,88	40143	273,0
GY01	10,3	6,9	18,8	1,84	25950	267,3
GY02	10,3	7,0	21,1	2,07	28709	295,7
GY03	9,9	6,8	21,2	2,08	30893	305,8
GY04	10,0	6,9	20,1	1,97	28577	285,8
GY05	9,3	6,8	15,8	1,55	24509	227,9

Mean Material G						
Sample Test	Absorbed energy [J]	J/m²	J/m	Stdev [J]	Stdev [J/m²]	Stdev [J/m]
GX0_mean	1,81	27913	262,4	0,08	6853	12,2
GY0_mean	1,90	27728	276,5	0,22	2511	30,7

Material H						
Sample Test	Width [mm]	Thickness [mm]	Absorbed energy [kpcm]	Absorbed energy [J]	J/m²	J/m
HX01	11,1	6,9	9,5	0,93	12168	135,1
HX02	10,6	6,9	10,6	1,04	14217	150,7
HX03	10,8	6,9	9,5	0,93	12506	135,1
HX04	10,5	7,0	9,0	0,88	12012	126,1
HX05	10,9	7,0	7,4	0,73	9514	103,7
HY01	9,9	7,0	8,8	0,86	12457	123,3
HY02	10,7	6,9	8,5	0,83	11294	120,8
HY03	10,1	7,0	9,1	0,89	12627	127,5
HY04	10,4	7,0	8,9	0,87	11993	124,7
HY05	10,2	7,1	8,4	0,82	11379	116,1

Mean Material H						
Sample Test	Absorbed energy [J]	J/m²	J/m	Stdev [J]	Stdev [J/m²]	Stdev [J/m]
HX0_mean	0,90	12083,6	130,1	0,11	1684	17,2
HY0_mean	0,86	11949,9	122,5	0,03	607	4,3

Odour Test Results

Odour Rating				
	Person 1	Person 2	Person 3	Person 4
AX11	2,5	1,5	3	2,5
AX21	3,5	2	3,5	3
BX11	3	2	3	3,5
BX21	4,5	2,5	3,5	4
CX11	3,5	4,5	3,5	4
CX21	4,5	3	4	4
EX11	1,5	2	2	2,5
EX21	3	3	3	2,5
GX11	5,5	5	3,5	4,5
GX21	5,5	5	4,5	4,5
HX11	3,5	4	3	3
HX21	4,5	3	4	3

Mean Values	
Sample	**Value**
AX11	2,375
AX21	3
BX11	2,875
BX21	3,625
CX11	3,875
CX21	3,875
EX11	2
EX21	2,875
GX11	4,625
GX21	4,875
HX11	3,375
HX21	3,625

Appendix E – Component Cost Calculation

Cost Calculation Dateils			Comments	
Fortus 380mc	Aquisition cost + 1 year warranty [SEK]	820000	Running time /year [h]	6720
	Depreciation cost [SEK/8 year]	452414		
	Warranty and Service [7 years]	490000		
	Equipement cost [SEK/h]	33		
Material FDM	Recycled/Bio filament [SEK/kg]	742	Density [g/cm3]	1,045
	ABS filament (reference) [SEK/kg]	707	Density [g/cm3]	1,02
Energy	Electricity [SEK/kWh]	0,8	Consumption [kWh/kg]	84,7
Labour	[SEK/hour]	350	Includes: preparation, loading and unloading	

Exchange rates	
American dollar, 1 $	8,90 kr
Euro, 1	10,85 kr

Details		
Production Volume		50
Post processing job		Not included
Generated waste material [%]		5

Manufacturing Data

Item	Buildable units/tray	Unit volume including support mateiral and waste [cm3]	Unit weight inlcuding support material and waste [kg]	Full tray manufacturing time [h]	Labour time [h]	Production time per part [h]
Integration Unit (recycled)	50	2,3310	0,00244	10	0,5	0,2100
Integration Unit (reference)	50	2,3310	0,00238	10	0,5	0,0100

Cost Detail

Item	Equipment	Material	Energy	Processing	Unit production cost	Total production coast
Integration Unit (recycled)	6,6	1,8	0,2	3,5	12,0	601,5
Integration unit (reference)	6,6	1,7	0,2	3,5	11,9	594,9

Appendix F – Sustainability Assessment

Material data					
Parameter	**Unit**	**ABS-M30**	**Material Recycled**	**Material Bio-based**	**Source**
Recycled fraction, raw material	%	0	95	0	N/A
Energy usage, raw material production	MJ/kg	95	95	52	CES
Energy usage, filament extrusion	MJ/kg	5,8	5,8	5,8	CES
CO2 footprint, raw material production	kg/kg	3,7	3,7	2,7	CES
CO2 footprint, filament extrusion	kg/kg	0,45	0,45	0,45	CES
NOx creation, raw material production	g/kg	13,6	13,6	1,6	CES
SOx creation, raw material production	g/kg	40,6	40,6	5,0	CES
Water usage, raw material production	l/kg	176	176	2370	8
Energy usage, waste collection	MJ/kg	0,2	0,2	0,2	CES
Energy usage, sorting of waste	MJ/kg	0,5	0,5	0,5	CES
Energy usage, recycling	MJ/kg	32,5	32,5	32,5	CES
CO2 footprint, recycling	kg/kg	1,2	1,2	1,2	CES
Heat of combustion (material energy content)	MJ/kg	38,4	38,4	19,4	CES
Combustion CO2 footprint	kg/kg	3,1	3,1	1,9	CES
Material density	kg/m3	1027	1045	1240	Measurement
Component mass	kg	0,00170	0,0017274	0,0020497	N/A
Waste factor (% production waste per component)	%	5	5	5	CES
Energy usage, FDM-process	MJ/kg	305	305	305	6
CO2 footprint, FDM-process	kg/kg	34,2	34,2	34,2	1
Water usage, recycling	l/kg	10	10	10	3

Life cycle data			
Parameter	**Unit**	**Value**	**Source**
Alpha (OECD 2015)	CO2/MJ	0,112	1
Combustion efficiency		0,25	CES
End of life recycled amount	%	10	CES
End of life combustion amount	%	90	CES
Car lifetime	Years	15	
Car distance traveled per year	km	12240	2
Energy consumption, hybrid car	MJ/tonne/km	1,1	CES
CO2 footprint, transport	kg/MJ	0,071	CES
Energy consumption, sea freight	MJ/tonne/km	0,16	CES
Energy consumption, truck	MJ/tonne/km	0,46	CES
Primary material transport distance, truck	km	1000	
Primary material transport distance, sea freight	km	0	
Component transport distance, truck	km	50	
Component transport distance, sea freight	km	0	
End of life transport distance, truck	km	600	7
End of life transport distance, sea freight	km	0	
NOx creation, passenger car (Euro 6)	g/km	0,06	4
NOx creation, truck (Class III truck, Euro 6)	g/km	0,125	4
Approximate truck weight when loaded	kg	21000	5
Approximate car weight	kg	1500	

Environmental impact assessment - ABS-M30 (Reference)					
Life cycle strage	Energy usage [MJ]	CO2 emissions [kg]	NOx creation [g]	SOx creation [g]	Water consumption [l]
Material production	0,180458175	0,00741	0,0242	0,0724	0,3137
Raw material production	0,1693	0,00660	0,0242	0,0724	0,3137
Transport	0,0008	0,00006			
Filament extrusion	0,0103	0,00076			
Manufacturing	0,01	0,00086			
FDM-process	0,0103	0,00080			
Post processing					
Transport	0,0008	0,00006			
Use	0,34	0,02434			
Use in car	0,3429	0,02434			
End of life	-0,02	0,00277			
Transport	0,0008	0,00006			
Material collection	0,0004	0,00005			
Recycling	-0,0114	-0,00046			
Combustion	-0,0147	0,00312			
Total	0,51	0,03539	0,0242	0,0724	0,3137

Environmental impact assessment - Re:Add ABS					
Life cycle strage	Energy usage	CO2 emissions	NOx creation	SOx creation	Water consumption
Material production	0,08	0,00324	0,0012	0,0037	0,0332
Raw material production	0,0646	0,00240	0,0012	0,0037	0,0332
Transport	0,0008	0,00006			
Filament extrusion	0,0105	0,00078			
Manufacturing	0,01	0,00087			
FDM-process	0,0105	0,00082			
Post processing					
Transport	0,0008	0,00006			
Use	0,35	0,02477			
Use in car	0,3489	0,02477			
End of life	-0,01	0,00325			
Transport	0,0008	0,00006			
Material collection	0,0004	0,00005			
Recycling	-0,0008	-0,00003			
Combustion	-0,0149	0,00318			
Total	0,42	0,03213	0,0012	0,0037	0,0332

Environmental impact assessment - PLA					
Life cycle strage	Energy usage [MJ]	CO2 emissions [kg]	NOx creation [g]	SOx creation [g]	Water consumption [l]
Material production	0,1253	0,0068	0,0035	0,0108	5,1007
Raw material production	0,1119	0,0058	0,0035	0,0108	5,1007
Transport	0,0009	0,0001			
Filament extrusion	0,0125	0,0009			
Manufacturing	0,0134	0,0010			
FDM-process	0,0125	0,0010			
Post processing					
Transport	0,0009	0,0001			
Use	0,4140	0,0294			
Use in car	0,4140	0,0294			
End of life	-0,0120	0,0023			
Transport	0,0009	0,0001			
Material collection	0,0005	0,0001			
Recycling	-0,0045	-0,0003			
Combustion	-0,0089	0,0025			
Total	0,5407	0,0395	0,0035	0,0108	5,1007

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Appendix G – Sustainability Assessment Calculations

In this document, all major calculations used in the sustainability assessment are described. The CO_2-emission values calculated are all CO_2-equivalents as described in the complete report. All calculations is done according to the method used in CES Eco Audit tool.

Calculations of energy usage of raw material production (H_{grade}) when using a fraction of recycled material.

$$H_{grade} = (\frac{100-R_f}{100} H_m + \frac{R_f}{100} H_{rc}) \frac{100+w_f}{100} m \qquad \text{[kg]}$$

Where

H_m = Energy usage during raw material production [MJ/kg]
R_f = Recycled fraction [%]
H_{rc} = Energy usage during of recycling process [MJ/kg]
w_f = Percentage of waste per component [%]
m = Mass of component [kg]

Calculations of water consumption of raw material production (W_{grade}) when using a fraction of recycled material.

$$H_{grade} = (\frac{100-R_f}{100} W_m + \frac{R_f}{100} W_{rc}) \frac{100+w_f}{100} m \qquad \text{[l]}$$

Where

W_m = Energy usage during raw material production [l/kg]
R_f = Recycled fraction [%]
W_{rc} = Energy usage during of recycling process [l/kg]
w_f = Percentage of waste per component [%]
m = Mass of component [kg]

Calculations of CO_2-eq emissions during raw material production (CO_{2grade}) when using a fraction of recycled material.

$$CO_{2grade} = \left(\frac{100-R_f}{100} CO_{2m} + \frac{R_f}{100} CO_{2rc}\right) \frac{100+w_f}{100} m \qquad \text{[kg]}$$

Where

CO_{2m} = CO_2 emissions during raw material production [kg/kg]
CO_{2rc} = CO_2 emissions during recycling process [kg/kg]

Calculations of energy usage (H_{usage}) due to the weight added to the car during car usage phase.

$$H_{usage} = L_{car} \cdot d_{car} \cdot H_{car} \qquad \text{[MJ/kg]}$$

Where
L_{car} = Car lifetime [years]
d_{car} = Distance travelled by the car per year [km]
H_{car} = Energy usage of the car during the [MJ/tonne/km]

Calculations of energy usage during transport

$$H_{transport} = d_{truck} \cdot H_{truck} + d_{sea} \cdot H_{sea} \qquad [MJ/kg]$$

Where
d_{truck} = Transport distance by truck [km]
d_{sea} = transport distance by sea freight [km]
H_{truck} = Energy usage of truck [MJ/tonne/km]
H_{sea} = Energy usage of sea freight ship [MJ/tonne/km]

Calculations of energy usage to collect material for after life treatment ($H_{collect}$).

$$H_{collect} = \frac{H_c + H_{ps} + H_{ss}}{100} r + H_c\left(1 - \frac{r}{100}\right) \qquad [MJ/kg]$$

Where
r = percent of material recovered at end of life [%]
H_c = Energy usage for collection of material [MJ/kg]
H_{ps} = Energy usage for primary material sorting [MJ/kg]
H_{ss} = Energy usage for secondary material sorting [MJ/kg]

Calculations of the energy ($H_{combust}$) and CO_2 ($CO_{2combust}$) produced at incineration of material.

$$H_{combust} = -H_{cal} \cdot Comb_{eff} \frac{r}{100} \qquad [MJ/kg]$$

$$CO_{2combust} = (CO_{2cal} - \alpha \cdot Comb_{eff} \cdot H_{cal}) \frac{r}{100} \qquad [kg/kg]$$

Where
H_{cal} = Energy content in material [MJ/kg]
$Comb_{eff}$ = Efficiency of the combustion process
CO_{2cal} = CO_2 “stored” in the material which is released when incinerated [kg/kg]
r = percent of material recovered at end of life [%]
α = CO_2 produced per MJ energy used [kg/MJ]

Calculation of CO_2 emissions from energy production.
If no other CO_2 calculation method is presented, the following general formula was used for relating the energy demand (H) to CO_2-eq emissions ($_{CO2}$).

$$CO_2 = H \cdot \alpha \qquad [kg/kg]$$

Where
α = CO_2 produced per MJ energy used [kg/MJ]