TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Mechanical and Industrial Engineering

SUSTAINABLE REPAIRING SOLUTION: THE ROLE OF 3D PRINTING IN REPAIRING CARS IN REPAIR SHOPS

JÄTKUSUUTLIK REMONDILAHENDUS: 3D PRINTIMISE ROLL REMONDITÖÖKODADES AUTODE PARANDAMISEL

MASTER THESIS

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Tallinn, 2023

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DEPARTMENT OF MECHANICAL AND INDUSTRIAL ENGINEERING

THESIS TASK

Student: Meelis Rikko;204686MARM

Study programme: MARM Industrial Engineering and Management

Supervisor(s): Tauno Otto, Tenured Full Professor, 6203266

Thesis topic:

(in English) – "Sustainable repairing solution: The role of 3D printing in repairing cars in repair shops"

(in Estonian) "Jätkusuutlik remondi lahendus: 3D-printimise roll remonditöökodades autode parandamisel"

Thesis main objectives:

1. Understand the benefits and limitations of 3D printing adoptation.
2. Assess the environmental impact of 3D printing in the automotive repair industry.
3. Identify potential barriers and challenges faced by repair shops when adopting 3D printing technology, such as technical expertise, material needs, waste management and equipment investments.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	3D printing field research and analysis.	19.03.23
2.	Identify automotive industry challenges and the current situation considering 3D printing for repair parts.	16.04.23
3.	Conduct interviews and surveys with repair shop owners and technicians.	30.04.23
4.	Analyse findings and barriers to summarise research.	14.05.23

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PREFACE

The idea for this master's thesis, "Sustainable repairing solution: The role of 3D printing in repairing cars in repair shops," was initiated by author Meelis Rikko. The inspiration behind this research arose from the growing global concern about sustainability and the potential of 3D printing technology to revolutionise various industries, including the automotive repair sector.

The study aimed to comprehensively analyse the potential impact of incorporating 3D printing into the automotive repair industry by examining various crucial aspects. First and foremost, the author evaluated the benefits and limitations of using this advanced technology to measure its current capacity accurately. In addition, attention was paid at how environmentally friendly it is for companies in this sector to employ such methods because sustainability has become increasingly important across industries worldwide. Moreover, the research assessed whether any factors could facilitate or restrain adoption within this field.

The study applied a mixed-methods approach, utilising interviews with repair shop owners to comprehensively understand the industry needs and insights. A questionnaire was also distributed to repair shop workers to investigate their awarenesses regarding the potential usage and advantages of 3D printing technology. The study examined repair shops' complications and limits when using 3D printing and factors that keep the industry from using it more widely.

Keywords: 3D printing, automotive repair, sustainable manufacturing, car repair shops, master thesis

LIST OF ABBREVIATIONS AND SYMBOLS

% - Percentage

3D - Three Dimensional

ABS - Acrylonitrile Butadiene Styrene

CAD - Computer-Aided Design

DfE - Design for the Environment

DLP - Digital Light Processing

DMLS - Direct Metal Laser Sintering

FDM - Fused Deposition Modelling

FFF - Fused Filament Fabrication

ISO - International Organization for Standardization

LCA - Life cycle assessment

MJ - Material Jetting

mm - millimetre

PA11 - Plastic Polyamide

PETG - Polyethylene Terephthalate Glycol

PLA - Polylactic Acid

SLA - Sterthography

SLS - Selective Laser Sintering

STL - Standard Triangle Language

TBL- Triple Bottom Line

1. INTRODUCTION

The automotive repair industry is a crucial sector that ensures the effective operation and durability of vehicles. Concerns have been raised regarding waste generation, resource consumption, and environmental impact due to the traditional methods of manufacturing and repairing auto parts. As the world moves toward more sustainable practices, it is essential to investigate innovative technologies that can revolutionise the automotive repair industry while minimising its environmental impact. This thesis examines the possible benefits and limitations of 3D printing when implementing a sustainable future in auto repair shops.

In recent years, 3D printing's potential to disrupt conventional manufacturing processes has garnered considerable attention. By enabling the layer-by-layer construction of objects from various materials, 3D printing technology provides numerous advantages, such as reduced waste, energy efficiency, and the ability to create complex geometries easily. 3D printing offers a promising alternative to the lengthy lead times for sourcing parts, high costs, and difficulties associated with repairing older or rare vehicles in the automotive repair industry.

This thesis, titled "Sustainable repairing solution: The role of 3D printing in automotive repair shops," seeked to analyse the potential benefits and challenges of implementing 3D printing technology in automotive repair shops. This research aimed to determine the essence and potential impact of 3D printing in automotive repair by analysing sustainable manufacturing principles, the history and evolution of 3D printing, and its current applications in the automotive industry.

Two research methodologies were used to achieve the work's objective and provide answers to research questions, where data were collected using quantitative and qualitative methods. Through interviews with repair shop owners and questionnaires completed by repair shop employees, the study also collected valuable information about the perspectives and experiences of industry professionals regarding the use of 3D printing for automotive repairs.

The author distributed a questionnaire survey to obtain rich insights for this research due to its potential to engage many knowledgeable individuals in the automotive sector. By doing so, it was possible to gather extensive information from diverse industry professionals whose input enriched the data-gathering process significantly. The survey had ten questions whose scope covered multiple issues related to the area of interest, facilitating thorough coverage during analysis while producing informative and various data sets.

One-on-one interviews were executed as part of the qualitative research method. It aimed to provide a deeper, more nuanced understanding of the subject matter because it was exploratory and focused on capturing insights, experiences, and motivations that determine behaviours and attitudes towards 3D printing.

Thesis main objectives:

- Understand the benefits and limitations of 3D printing adoption
- Assess the environmental impact of 3D printing in the automotive repair industry
- Determine industry readiness for 3D printing technology
- Analyse the cost-effectiveness of 3D printing in the automotive industry

According to the author, the research results will benefit several companies and repair shops that operate in the car repair industry. Based on the research and its results, the repair shop owners can assess their company's ability and need for a 3D printer. From the results of this work and the study, companies engaged in car repair can also find out what analyses and activities should be carried out in advance and what other advice should be used before the purchase of a 3D printer is decided.

2. SUSTAINABLE MANUFACTURING AND 3D PRINTING TECHNOLOGY

2.1 Sustainable manufacturing background

Sustainable manufacturing refers to a method of industrial production that prioritises environmental impact reduction, waste minimisation, energy conservation, and optimal resource utilisation throughout the entire product lifecycle. The concept arose due to rising concerns regarding conventional manufacturing methods' negative environmental and societal effects of conventional manufacturing methods. These effects include pollution, depletion of natural resources, and worsening global warming. According to the Triple Bottom Line (TBL) paradigm, sustainable manufacturing seeks to balance economic growth, ecological preservation, and social responsibility. (Slaper, Hall, 2011)

The genesis of sustainable manufacturing occurred in conjunction with the early stages of environmentalism between 1960-70. As public realisation regarding ecological degradation increased, numerous international agreements, including Brundtland Report(1987), United Nations, Rio Earth Summit(1992), and Paris Agreement(2015), were introduced to tackle these issues by promoting eco-conscious initiatives through sustainable development worldwide. (Velenturf, Purnell, 2021)

Sustainable manufacturing is a broad concept that encompasses diverse approaches and methods, which include:

- The concept of resource efficiency involves optimising the usage of raw materials, water, and energy during the production process to reduce waste and consumption of nonrenewable resources.
- Adopting environmentally sustainable technologies and processes to minimise pollution and emissions, prevent the release of hazardous substances, and reduce the overall environmental impact of manufacturing activities is referred to as cleaner production.
- Design for the Environment (DfE) is a process that integrates environmental considerations into the product design. This includes utilising sustainable materials, increasing the product's recyclability, and minimising energy consumption during its use phase.
- Life cycle assessment (LCA) is a technique used to evaluate the environmental impact of a product throughout its entire lifetime. This encompasses extracting

raw materials, production, distribution, utilisation, and disposal. LCA aims to identify improvement areas and minimise negative environmental impacts.

- The circular economy is a paradigm shift from the linear approach of "take-make-dispose" to a system that emphasises the continuous reuse, recycling, and regeneration of resources. This strategy aims to increase product durability and reduce waste. (Moldavska, Welo, 2017)

In recent times, there has been a marked advancement in scientific innovations to produce environmentally responsible goods using unconventional techniques. Additive manufacturing or 3D printing is one such innovation that could transform traditional product development methods to enhance sustainability across various industries. Through our research investigation, we aim to examine how this novel technology could help reduce wastage and optimise material use for more sustainable manufacturing processes.

2.2. The overview of 3D printing technology

Through the utilisation of additive manufacturing techniques, commonly known as 3D printing, the process of producing solid three-dimensional objects has been redefined entirely. Rather than removing or altering pre-existing matter through subtraction-based methods such as milling or cutting, creators can add layers of materials sequentially in response to digital schematics using this groundbreaking method. This innovation is widely recognised as transformative not only due to impeccable customizability and because it can efficiently decrease raw material expenditure and waste production.(Savini, Savini, 2015)

Sterthography (SLA) was a revolutionary idea brought to life by Charles Hull during the early days of modern-day three-dimensional printing back in the 80s. Ever since, numerous alternative solutions for additive manufacturing have been introduced, all with different trade-offs and benefits. Amongst them are some prevalent techniques, including

- One of the most prevalent methods in modern-day 3D printing processes is Fused Deposition Modelling (FDM). With each layer deposited according to digital commands via extruding thermoplastic filaments from a heated nozzle onto a designated platform, its popularity continues to grow thanks to its relative ease of use and affordability when compared to other additive manufacturing techniques. This adaptability across multiple materials is another reason individuals and enterprises alike turn towards FDM when undertaking endeavours such as prototyping or even small-scale production.
- Stereolithography (SLA) is a photo polymerisation process involving selective curing of a liquid resin by an ultraviolet light source. This procedure leads to the gradual solidification of the material, layer by layer, ultimately forming the final object. SLA is renowned for its exceptional precision and resolution, which makes it a viable option for tasks requiring intricate details and polished surface textures.
- Selective Laser Sintering (SLS) is a manufacturing process that involves fusing powdered materials, such as nylon or metal, layer by layer using a high-powered laser. The technology mentioned above is ideally suited for fabricating functional components with complex geometries and exceptional strength and durability. In addition, it generally does not require the use of support structures.
- Digital Light Processing (DLP) is a type of Stereolithography (SLA) that employs a digital light projector to solidify photosensitive resin layer by layer selectively. DLP technology is renowned for its exceptional printing speed and accuracy, making it suitable for applications requiring intricate details and precision.
- Material Jetting (MJ) is a technology involving the deposition of droplets of various substances, such as photopolymers, wax, or metal. Subsequently, these droplets are cured or solidified using UV light or other suitable techniques. As mentioned previously, the procedure facilitates the printing of multiple materials and enables the production of high-resolution, full-colour models (Ngo et al. 2018) (Sculpteo, 2023).

With the advent of cutting edge technologies in 3D printing it is now possible to utilise a wide variety of materials that include plastics, metals, ceramics and biomaterials. In recent times this progress towards innovation has been remarkable. The versatility offered by this technology has created various possibilities for different industries ranging from aerospace to automotive and from healthcare to consumer goods as well as construction.

Additionally, the constant progress towards developing this tech holds significant promise for enabling sustainable manufacturing procedures through reducing material waste while increasing energy efficiency levels accompanied by localised production capabilities.

3. THE AUTOMOTIVE SECTOR AND SUSTAINABILITY

3.1. Description and sustainable manufacturing principles

Sustainable manufacturing is an approach to industrial production that prioritises the reduction of negative environmental impacts, the maximisation of resource efficiency, and the promotion of social accountability, all while maintaining economic viability. Commonly known as the Triple Bottom Line (TBL) paradigm, sustainable manufacturing seeks to balance economic growth, environmental preservation, and social equity. Incorporating sustainability principles into manufacturing operations can improve firms' long-term competitiveness, reduce operational costs, and advance global efforts to mitigate climate change and conserve resources. (Reyes, 2022)

The principles related to sustainable manufacturing can be categorised into various areas such as:

1. Sustainable manufacturing hinges on efficiently exploiting available resources such as raw materials, water and energy. The key objective is to enhance resource optimisation in every production stage by minimising waste generation while encouraging maximum material usage. Implementing robust measures for recovering and reusing waste in addition to recycling safeguards further ensures there's limited resource depletion over time.

2. The principle of Cleaner Production entails adopting environmentally sustainable technologies and processes to mitigate pollution and emissions, averting the discharge of hazardous substances, and minimising the ecological impact of manufacturing operations. The implementation of cleaner production strategies involves the adoption of renewable energy sources, the reduction of greenhouse gas emissions, and the implementation of pollution control measures.

3. Design for the Environment (DfE) is a strategic methodology for product design that integrates environmental factors into the initial phases of product development. The strategies above encompass the employment of sustainable materials, enhancement of recyclability, minimisation of energy consumption during the product's usage phase, and contemplation of disposal alternatives at the end of its life cycle.

4. LCA, or life cycle assessment, is a systematic approach for assessing a product's environmental impact throughout its entire life cycle, from raw material extraction to end-of-life disposal. Manufacturers can find areas for improvement and implement strategies to reduce negative effects by understanding how products perform environmentally at each life cycle stage.

5. Sustainable manufacturing encourages the switch from a linear "take-make-dispose" model to a circular system where resources are continuously reused, recycled, and regenerated. Reducing waste and using non-renewable resources includes extending the lifespan of products through repair, refurbishment, and remanufacturing, as well as recycling and material reuse.

6. Sustainable manufacturing encompasses social responsibility by considering various aspects of production, including equitable labour practices, occupational health and safety, and community involvement. Organisations that prioritise social responsibility have the potential to improve their standing, draw in high-calibre personnel, and cultivate enduring connections with clients and stakeholders.

Sustainable manufacturing seeks to develop an industrial sector that is more environmentally friendly, socially responsible, and economically viable to support long-term business success while advancing global sustainability goals.

3.2. The development and history of 3D printing

The beginnings of the practice of additive manufacturing can be found in the 1980s, which was when 3D printing first became popular. The development of 3D printing technology can be broken down into several significant turning points that have influenced its growth and influence on numerous industries:

1. The inception of 3D printing can be traced back to the 1980s when Dr Hideo Kodama introduced the concept in his published work on a rapid prototyping technique utilising photopolymers. In 1984, Charles Hull submitted a patent application for stereolithography (SLA), which is regarded as the initial 3D

printing technology. Following his previous endeavours, Hull established 3D Systems in 1986 and subsequently introduced the inaugural commercial SLA 3D printer in 1988.

2. With advances in technology during the early part of the last decade into the late nineties, there were considerable developments in the realm of additive manufacturing, also known as three-dimensional (3D) printing techniques, that expanded its application to various fields with greater implementation opportunities for more diverse material usage demonstrated through innovative approaches such as Selective Laser Sintering (SLS) invented by Dr Carl Deckard and Dr Joe Beaman at University Of Texas - Austin coupled with Fused Deposition Modeling(FDM) pioneered by S Scott Crump in 1989 who later established Stratasys. The novel technologies enabled the utilisation of a wide range of materials, including thermoplastics and metals, thus enhancing the potential of 3D printing in multiple industries. (A, 2022)

3. During the 2000s, the 3D printing market experienced notable growth and expansion, characterised by the emergence of new companies and the exploration of additional applications. The RepRap project was introduced by Dr Adrian Bowyer in 2005 to create a self-replicating 3D printer through an open-source approach. The project significantly impacted the democratisation of 3D printing, increasing accessibility to the technology for hobbyists and small businesses.

4. Numerous events combined made way for the proliferation of 3D printing use today, including patent expiry followed by technological leaps forward that ultimately led to lower prices for consumers over time. Additionally, through brand innovation efforts from various manufacturers came an increase in more sophisticated models aimed at customers' individual needs during those early years. As we move into modern times, modernisation efforts have ensured that three-dimensional (3D) printing technology is now prevalent across multiple industry sectors ranging from manufacturing processes (such as aerospace) all the way down through medical devices needed for patient care purposes - not forgetting fashionable items too! The past decade saw groundbreaking moves with regards specifically towards new materials being incorporated, alongside complete departures from past practices in fields like bioprinting and construction.

5. The integration of Industry 4.0's most transformative technologies, such as IoT, AI, and Robotics, along with additive manufacturing processes like 3D printing,

has brought forth an array of possibilities for manufacturers striving towards a sustainable future since it enables and enhances intelligent, efficient, and eco-friendly production systems. With a focus on sustainability now more important than ever, the use of 3D printing is gaining traction in the manufacturing industry as a key tool to promote waste reduction, conserve energy, facilitate localised production networks and ultimately minimise the environmental impact of manufacturing processes.

Throughout its development, 3D printing has experienced notable progressions throughout its development, evolving from a specialised prototyping technique into a multifaceted manufacturing instrument that can transform various industries and promote sustainability. (Hu, Jiang, 2017)

3.3. The present state of sustainable manufacturing

The present condition of sustainable manufacturing is characterised by increasing consciousness and the implementation of environmentally friendly practices, technologies, and approaches. The escalating apprehensions regarding climate change, resource depletion, and pollution have led to a growing adoption of sustainability principles by industries globally. They have acknowledged the significance of incorporating these principles into their operations. In this particular context, 3D printing technology has emerged as an auspicious means of addressing various difficulties that conventional manufacturing methods frequently experience. Furthermore, it has the potential to make a significant contribution to the advancement of more sustainable practices. (Faludi et al. 2015)

The role of 3D printing in sustainable manufacturing can be examined across several dimensions:

1. Material Efficiency - Efficient use of resources is achievable with 3D printing technology as it offers significant advantages over more traditional methods of production. Layer-by-layer building allows for complex geometries with minimal waste by depositing only where required - resulting in decreased materials consumption and improved resource utilisation rates. These improvements are

highly relevant for sustainable manufacturing practices and contribute positively towards reducing long-term environmental impact.

2. Reduced Waste - The capability of 3D printing to create parts with fewer or no support structures, when combined with the possibility of digital optimisation of designs, can significantly reduce the amount of waste produced during production. In addition, 3D printing enables the recycling and reuse of waste materials generated during the printing process, contributing further to reducing waste and supporting the principles of circular economies.

3. Energy Efficiency - The use of 3D printing offers substantial benefits regarding energy efficiency - particularly when compared with conventional manufacturing procedures. The ability to print locally on demand drastically diminishes demands related to storage items or supplies. Adding to this value proposition are features inherent within additive manufacturing: the ability to produce lightweight parts that provide optimal performance benefits across various industries. By increasing energy efficiency during operation stages, such as those within the aviation or automotive sector, 3D printing technology ultimately decreases the amount of energy required for finished products.

4. Customization and Distributed Manufacturing - 3D printing allows for high levels of customisation and personalisation, enabling manufacturers to produce tailor-made products for specific customer needs. This can lead to reduced overproduction and inventory waste. Moreover, 3D printing supports distributed manufacturing models, where production can occur closer to the end consumer, reducing transportation-related emissions and environmental impacts.

5. Supporting Circular Economy - 3D printing can significantly promote the circular economy by facilitating product re refurbishment, and remanufacturing. By enabling the production of replacement parts on demand, 3D printing can extend the life of products, reducing waste and resource consumption.

There is no denying that utilising 3D printing has immense potential when it comes to achieving sustainability objectives within modern-day industry practices. However, there exists an acknowledgement that certain constraints may hinder this progress when dealing with renewable energy sourcing or material development where reducing carbon footprints becomes crucially important regarding emissions from printers themselves all over the world; continued technological improvements play a vital role in bringing about change towards more eco-conscious production systems that stand a better chance at protecting our planet for the long term.

4. 3D PRINTING ROLE IN SUSTAINABLE MANUFACTURING

4.1. Printing methods for 3D objects

The past few years have seen tremendous strides made forward in the world of three-dimensional (3D) printing technology; however, producing high-resolution metallic structures using a print medium remains one of its toughest challenges. Across many fields, including engineering, physics, material science, chemistry, biology and medicine, there's been considerable focus directed towards this area of innovation. Despite this active interest its common knowledge that all current approaches towards 3d metal printing are yet to be able to effectively tackle intricate metallic objects that have complex production requirements prompting doubts about their feasibility.

The basic premise underpinning any 3D printing technique is adding successive layers of material to create an object with individual strengths and weaknesses depending on factors like the materials employed level of intricacy involved as well as target production quality or velocity requirements etc. Thus far, different methods , each with their own respective upsides and drawbacks, have emerged over time. To gain greater insight into these diverse options, we will take a moment to highlight several proven 3D print technologies.

- Fused Deposition Modeling (FDM): renowned for its simplicity and cost-effectiveness, continues to stand out amongst other 3D printing techniques available today due to the extensive range of applications it offers. In this method, a thermoplastic filament is heated until melted before being extruded through a nozzle that moves along specific coordinates whilst fabricating an object one level at a time. Once done with one layer fabrication process ends with the lowering of the build platform with a continuation on the next level by the same method. It has become instrumental in various sectors, including educational institutions, for practical learning experiences or prototyping, thanks to how cheaply simple parts can be produced using this process.

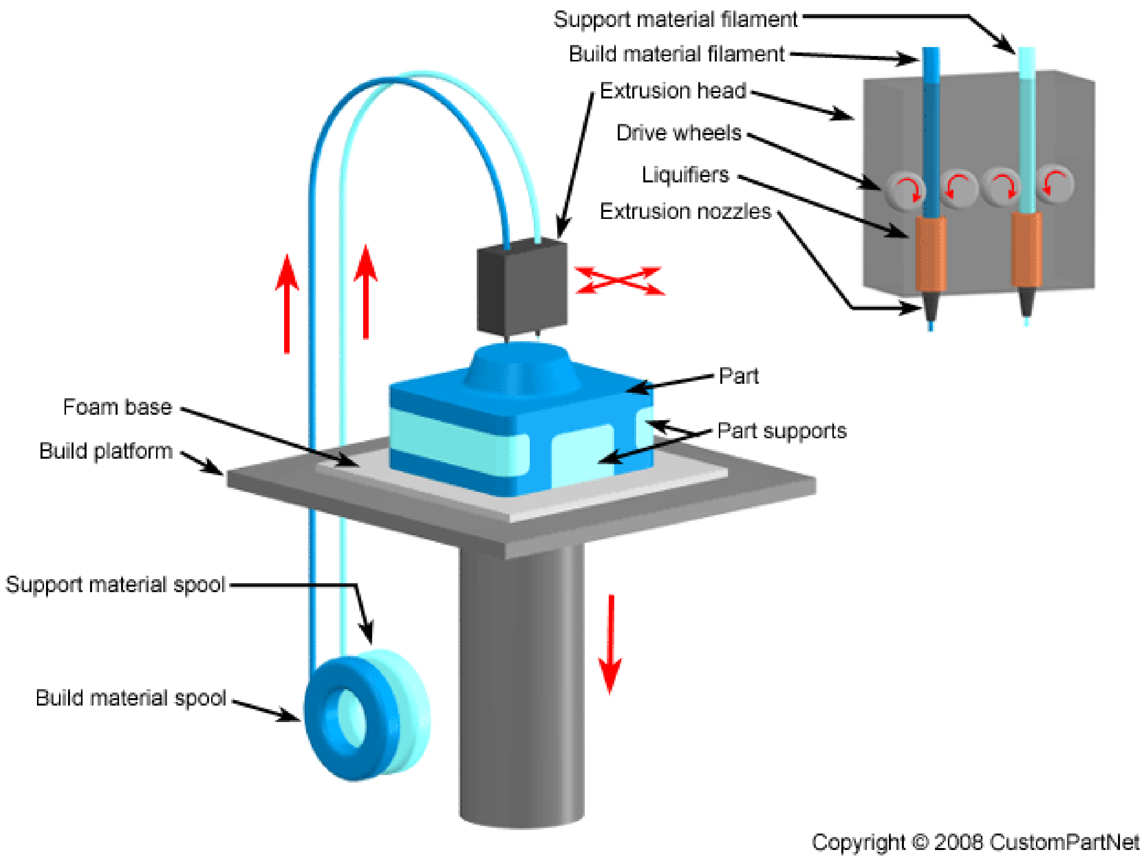


Figure 4.1 Fused Deposition Modeling (FDM) workflow. (Custompart, 2023)

- Stereolithography (SLA):

SLA is the oldest 3D printing technology, and it uses a process called photo polymerisation to create objects. In SLA, an ultraviolet (UV) laser beam is directed onto a vat of liquid photopolymer resin, which hardens when exposed to UV light. The laser traces the object layer by layer, and after each layer is complete, the build platform rises to allow the laser to create the next layer. SLA is known for its high precision and surface quality, making it suitable for creating detailed models and prototypes.

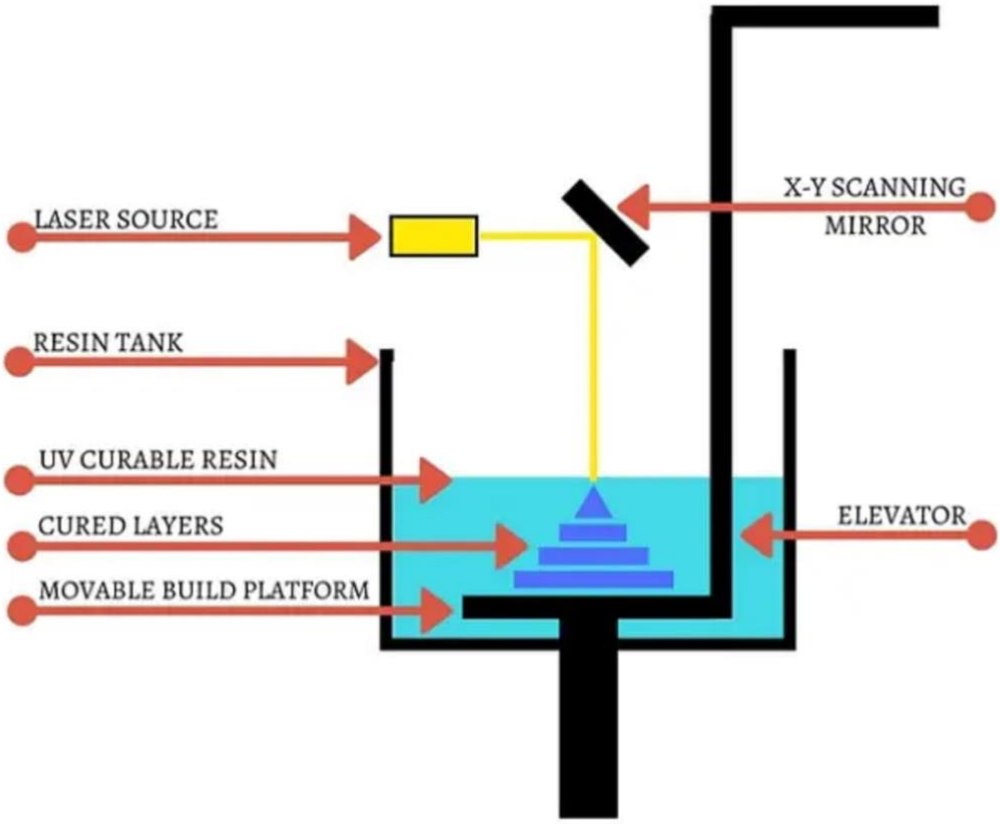


Figure 4.2 A Diagrammatical Representation of the working of SLA. (Manufactur, 2023)

- Selective Laser Sintering (SLS):

SLS is a powder-based 3D printing technique that uses a high-power laser to sinter powdered material, typically nylon or polyamide, into a solid structure. The laser selectively fuses the powder particles layer by layer according to the digital model. Once a layer is completed, a new layer of powder is spread over the previous layer, and the process continues. SLS does not require support structures because the surrounding unsintered powder provides support, allowing the production of complex geometries.

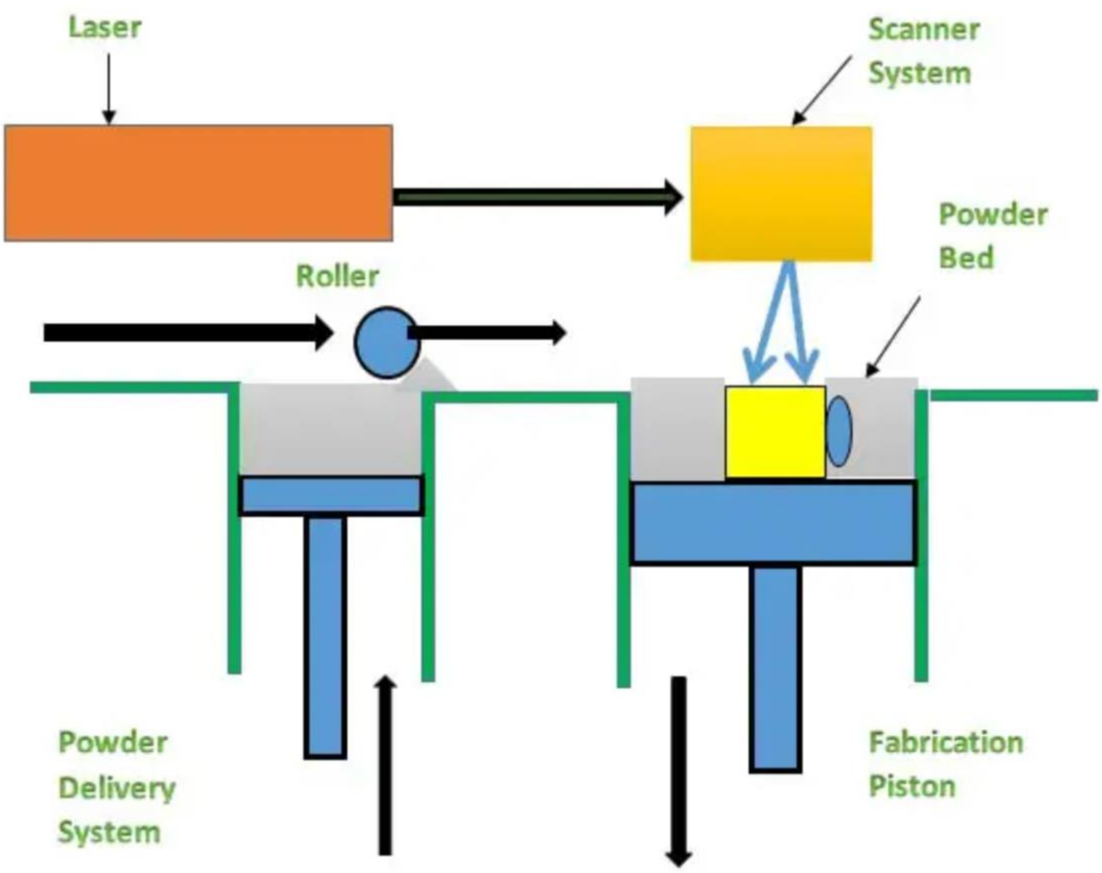


Figure 4.3 A Diagrammatic representation of the working of Selective Laser Sintering Technology. (Manufactur2, 2023)

- Direct Metal Laser Sintering (DMLS) or Selective Laser Melting (SLM):

DMLS and SLM are similar to SLS, but they are used to print metal objects. These techniques employ a high-power laser to fuse metal powder particles layer by layer. DMLS and SLM can create metal parts with complex geometries and internal structures, making them ideal for aerospace, automotive, and medical applications.

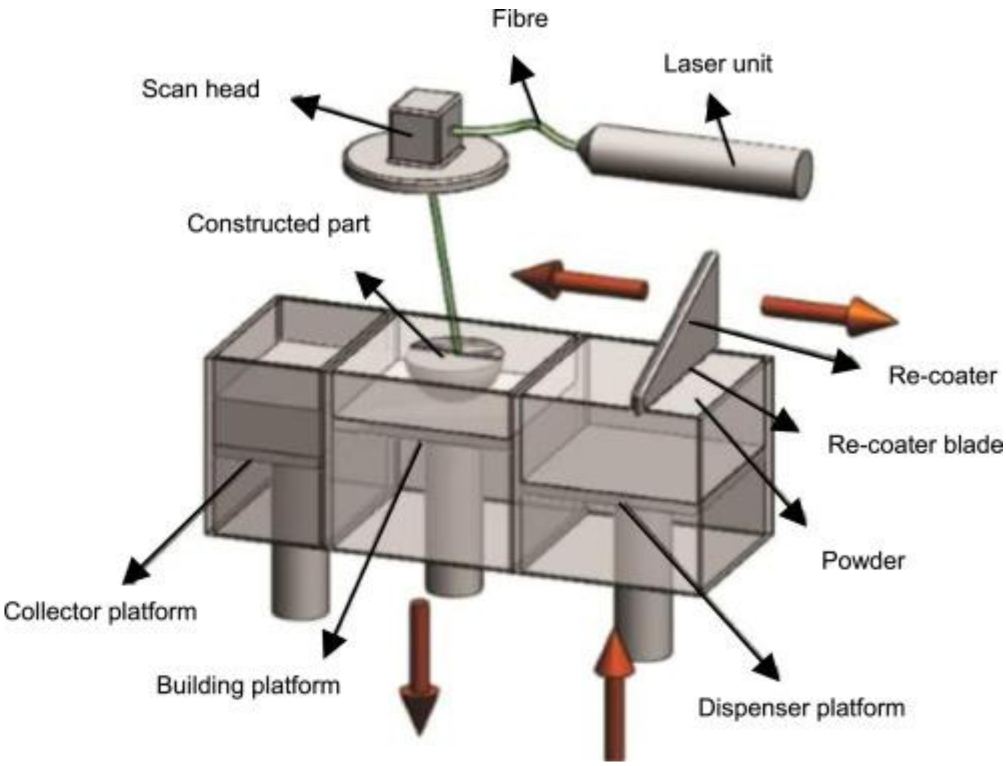


Figure 4.4 Schematic diagram of the DLMS process. (Bineli et al., 2011)

- Digital Light Processing (DLP):

Similar to SLA, DLP uses a digital light projector screen to flash an image of a layer across the entire platform at once, curing the resin. DLP can be faster than SLA, but the resolution can be less depending on the projector's quality.

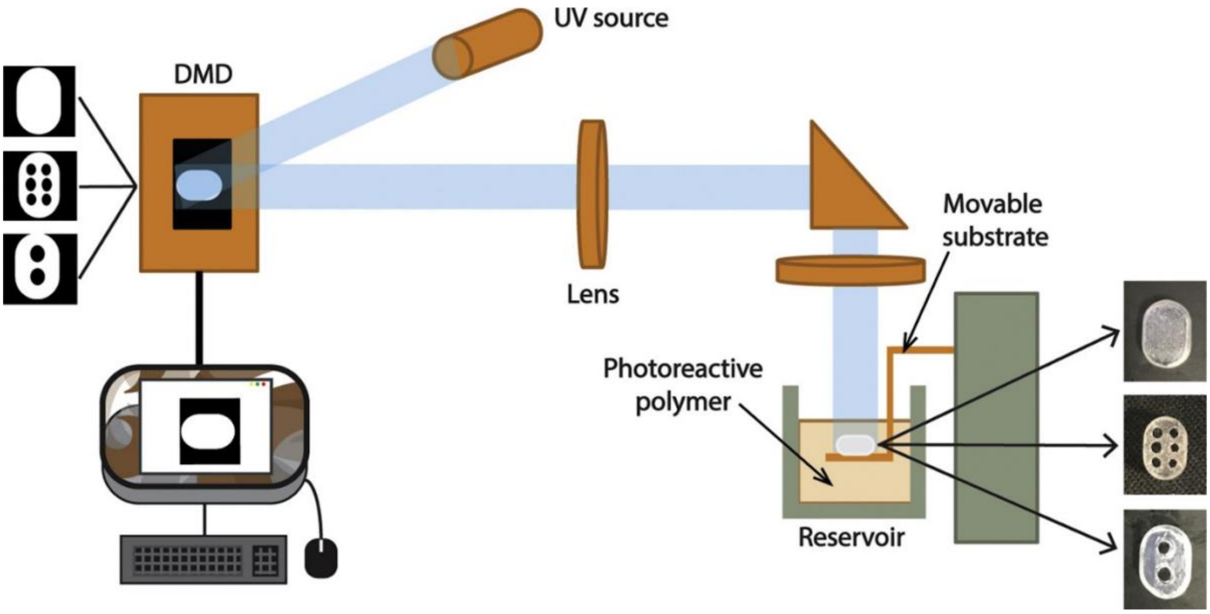


Figure 4.5 A schematic diagram of the Digital Micromirror Device (DMD) stereolithography setup. (Hossam et al., 2019)

- Electron Beam Melting (EBM)

Is an advanced metal 3D printing technology that utilises an electron beam to selectively melt metal powder in a layer-by-layer fashion. This process occurs within a vacuum chamber, where the build platform is heated to a predetermined temperature according to the material used. EBM offers several advantages and unique characteristics compared to other metal 3D printing techniques, such as Direct Metal Laser Sintering (DMLS) and Selective Laser Melting (SLM).

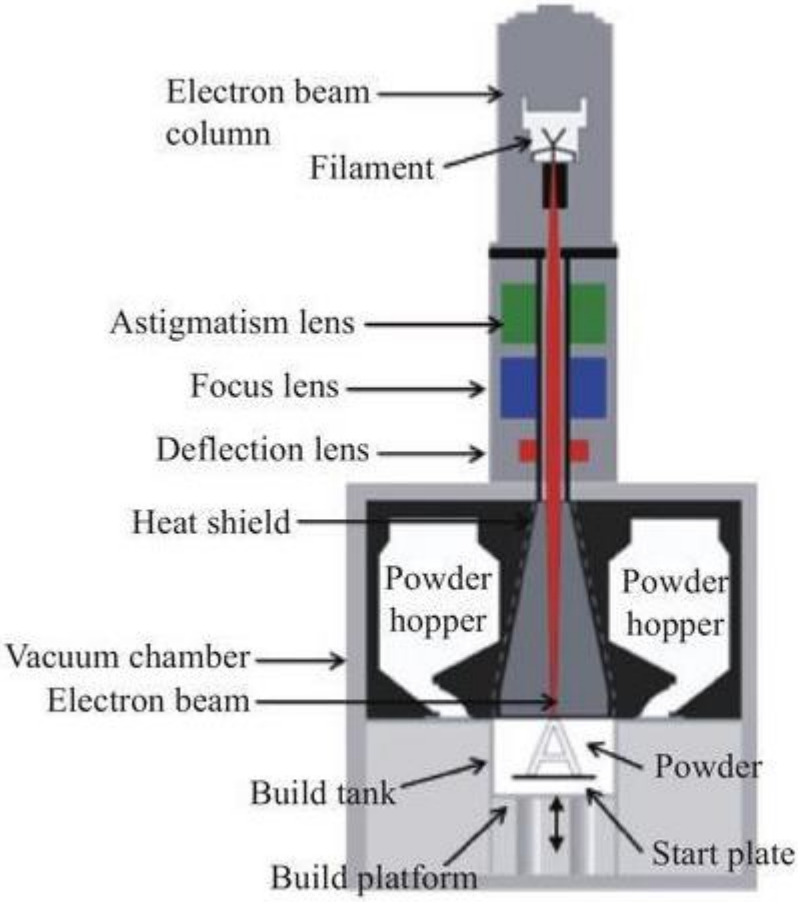


Figure 4.6 The principle of using the electron beam for melting metallic materials in the additive manufacturing process. (Truer, 2023)

To achieve optimal outcomes with 3D printing - careful consideration must be given regarding which method is chosen to facilitate it. This decision relies on various aspects such as material characteristics involved in production; size complexity or intricacies of components; final finish quality requirements sought by clients alongside financial restrictions that may apply during production runs. The future looks promising for additive manufacturing since ongoing technological innovations are expected to herald new methods, thereby broadening possibilities furthermore.

4.2 Material effectiveness and waste minimisation

There are two aspects to waste management: one is to reduce waste generated during production, and the other is to recycle old products to create new ones. Technology related to 3D printing is crucial to resolving this issue. A computer-generated design is used to produce three-dimensional (3D) objects using additive manufacturing (AM) technology. The market will move more quickly now that this new technology is available, and it will also be more affordable and less wasteful. Because it requires less production time, this technology enables the producer to meet customer demand. Additionally, the 3D printer serves as a tool for cutting waste and emissions. Additionally, it significantly strengthens the economy. A 3D printer can deal with both aspects of waste management. It reduces waste and recycles plastic waste into filaments for 3D printing. Technologies for 3D printing also have some limitations. Although some plastics cannot be recycled due to their polymer structure, almost all plastic types can be recycled to create 3D printing filaments. The main benefits of 3D printing technology in the plastic reforming industry are portrayed in Fig. xxxx.

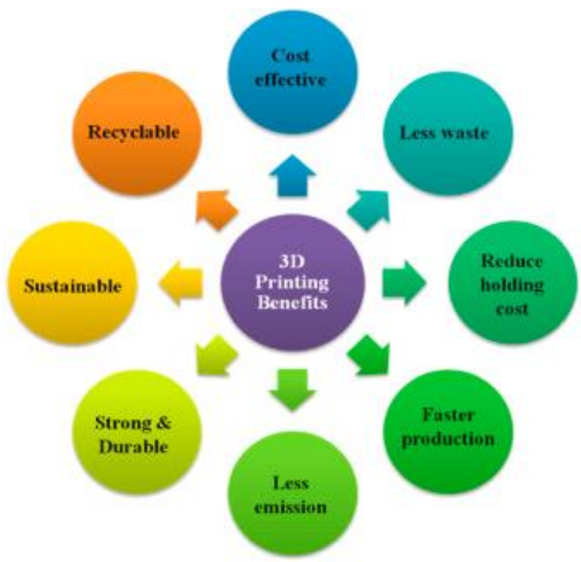


Figure 4.7 Benefits of 3D printing technology. (Abin, Umakanta, 2022)

4.3. Energy efficiency and reduction of carbon emissions

Many questions regarding energy and material consumption have recently been brought up due to the rapid development of AM and its applications. The research of thermal engineering and thermoforming is the subject of many papers. Typically, the thermoplastic material comes as a filament or pellet. The viscous material is extruded onto the substrate layer after being heated in the extruder to a temperature above the melting point. Extruded material can bond with the preceding layer while its temperature is higher than its glass transition temperature. The mechanical properties improve as the bond between layers becomes stronger. (Dinwiddie et al., 2014), (Colbert, 2014)

Reducing carbon emissions and optimising energy efficiency are integral aspects of sustainable manufacturing, given their direct impact on mitigating climate change and preserving resources. By leveraging 3D printing technology manufacturers can make significant strides in enhancing energy efficiency while curtailing carbon emissions via several mechanisms:

1. The capacity of 3D printing to generate intricate and efficient geometries that are not feasible or cost-effective through conventional manufacturing techniques is regarded as a significant benefit of lightweight design. The ability mentioned above facilitates the creation and manufacturing of low-weight constituents, particularly in sectors like aviation and automobiles. Utilising lighter components leads to decreased energy consumption and reduced carbon emissions in the usage stage of commodities. This is because less energy is needed for both transportation and operation.

2. The potential of 3D printing as an additive manufacturing process to considerably decrease material waste compared to subtractive manufacturing methods is noteworthy. 3D printing reduces waste generation and promotes the efficient utilisation of resources by selectively depositing material solely in the required areas. The aforementioned outcome results in a decrease in energy consumption and a reduction in carbon emissions that are linked to the extraction, processing, and disposal of materials.

3. Taking advantage of 3D printing technology allows the implementation of distributed manufacturing, which in turn results in the reduction of the necessity for the transportation of goods and raw materials over long distances. The utilisation of 3D printing technology can potentially reduce the energy consumption and carbon

emissions linked with transportation and logistics by enabling manufacturing to be situated closer to the point of consumption.

4. Support for Renewable Energy: To support sustainable practices in the energy industry, many companies are turning to renewable forms of energy - and 3D printing technology has emerged as a key player in this trend. While acknowledging that there are some environmental costs associated with manufacturing via 3D printers, we should focus on its positive contribution to promoting eco-friendly alternatives like solar panels and wind turbines by providing essential components, including mounting units and turbine blades.

5. Production that uses less energy: New developments in 3D printing technology have increased the production process's ability to use less energy. For instance, more recent 3D printers might use less energy to warm up materials or cure layers, reducing energy use and the associated carbon emissions.

Potential gains from utilising 3D printers for promoting sustainability notwithstanding, it should be kept in mind that this method doesn't always represent a catch-all solution for boosting energy efficiency or mitigating carbon emissions. With factors ranging from printer specifications and input materials to utilisation tactics affecting its environmental performance, determining whether or not an implementation makes sense requires evaluating all relevant pros and cons on a granular level. This helps ensure optimal results by highlighting areas where innovation could improve upon current technologies.

AM, or additive manufacturing, is a method of creating objects from three-dimensional (3D) models by layering raw materials in the form of powder, liquid, sheets, or filaments without the use of moulds, tools, or dies. As a result, 3D printing raises issues regarding material and energy consumption.

Electrical energy is typically the most consumed when it comes to 3D printing. With a servo-controlled motion system and an auxiliary feed system, the material is heated layer by layer with thermal energy to complete additive manufacturing through the thermosetting effect. As a result, from an econometric perspective, 3DP is divided into three sub-systems: thermal, mechanical, and auxiliary, from which the energy and material consumption model of 3DP is constructed. (Jinghua et al., 2019)

Gebler et al. (2014) say that by 2025, industrial manufacturing could use up to 5% less energy and put out 5% less CO_2 if it used 3D printing instead of traditional methods. Compared to traditional ways of making things, the additive manufacturing style of 3DP can save a lot of energy and raw materials during the making process. Its decentralised way of making things is closer to the consumer and can reduce the carbon footprint because raw materials and finished products don't have to travel as far.

We can't ignore that 3D printing has a limited production capacity. This means that 3DP is better suited to work with traditional industrial mass production than to replace it completely. Because of this, more research needs to be done on the design, fabrication, materials, and participation patterns of 3D printing for manufacturing to figure out how it affects the environment and how to measure its life cycle.

5. THE ADVANTAGES AND OPTIONS OF 3D PRINTING FOR AUTOMOTIVE INDUSTRY

5.1. Size Restrictions and 3D Printing Capabilities for Repair Parts

One of the most significant advantages of 3D printing lies in its ability to produce complex structures that are otherwise impossible or difficult to manufacture with conventional techniques. As with every innovation, however, there are limits to its manufacturing capabilities.

The size of the smallest part possible through this technology primarily depends on the resolution of the selected printer; typically ranging from mere micrometres for high-resolution types like Stereolithography (SLA) and Digital Light Processing (DLP), which employ UV light layers curing photo-reactive resins together in highly intricate shapes - like tiny gears and connectors - required for mechanical components.

Evaluating quality with small prints can be useful; yet ensuring detail precision during production remains challenging for printers handling incredibly tiny objects. A Hungarian-based company named Basilikus 3D has efficiently produced smaller components using the Solidscape T76+ professional 3D printer, creating a 1/10 scale Marvin.

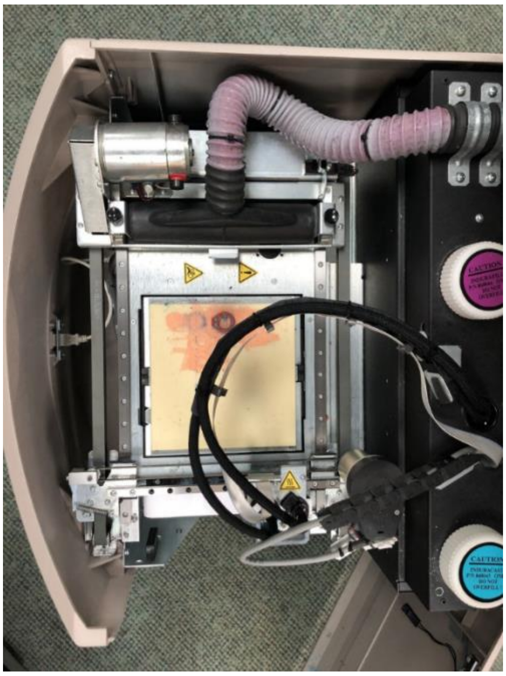


Figure 5.1 Solidscape T76+ 3D Printer. (eBay, 2023)

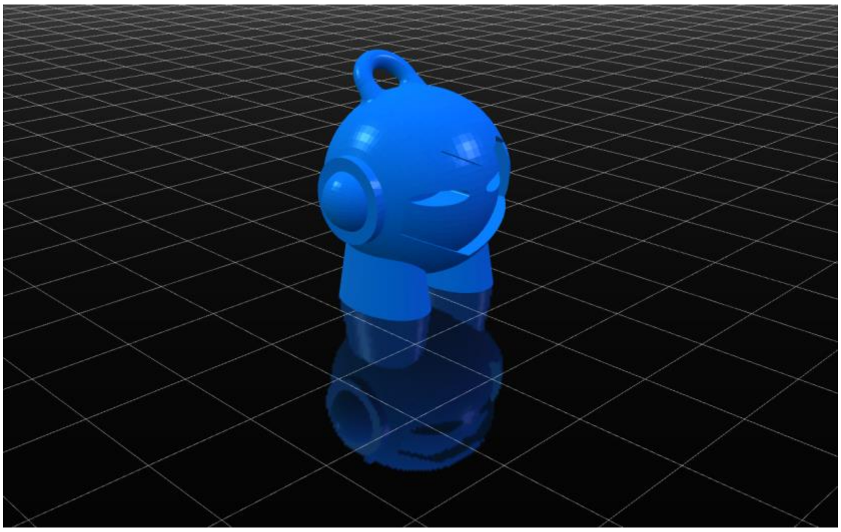


Figure 5.2 3D model of Marvin. (Thingiverse, 2023)

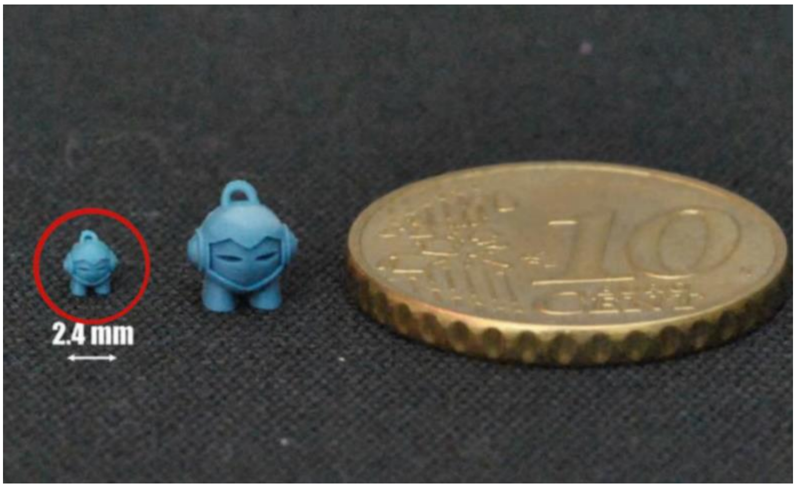


Figure 5.3 3D printed Marvin character compared with a 10-cent coin. (All3DP, 2023)

Many people print Marvin, a well-known 3D Hubs model, to evaluate the print quality of their printers. On the 1/10 scale model of the Marvin, as seen in the photo above, the ship's details are still discernible. The Solidscape T76+3D wax 3D printer, a professional wax 3D printer used to create jewellery models for casting, makes this possible and can produce incredibly intricate small pieces. The printing process took 4.5 hours with a layer thickness of 0.012 mm.

The largest solid 3D printed object was created on October 10, 2019, by The University of Maine Advanced Structures and Composites Center (USA) in Orono, Maine, United States, with a volume of $2.06m^3$.

Figure 5.4 3Dirigo - a 3D printed boat; University of Maine. (Guiness Wold Records, 2023)

The boat is known as 3Dirigo, after the motto of the state of Maine, which is "Dirigo," and it currently holds the record for the largest boat that has been printed using a 3D printer, according to Guinness World Records. (Guiness Wold Records, 2023)

To date, the size limitations of three-dimensional printing have been mainly attributed to the build volume of printers; this factor tends to dictate how large objects can be produced. When objects exceed printer capacities, options like specialised large-scale printers or segmental printing followed by the assembly are typically used. Optimistically speaking, though, industrial-grade additive manufacturing methods such as fused deposition modelling (FDM) or selective laser sintering (SLS) can produce parts with dimensions reaching several meters in both length and width. This is an exciting development because significant automotive components, such as entire vehicle chassis' can now be printed effortlessly using these techniques. Nevertheless, these advanced systems demand substantial investments as supplementary infrastructure for efficiency material handling and post-processing of output is often required.

An example of how much we can achieve through 3D printing in white plastic polyamide (PA11) with raw finish has measurements reaching roughly up to 677mm x 368mm x 565mm only. The right choice in terms of dimensions and factors, such as material type and finish, can be pivotal in achieving success when venturing into any project centred on 3D printing technology.

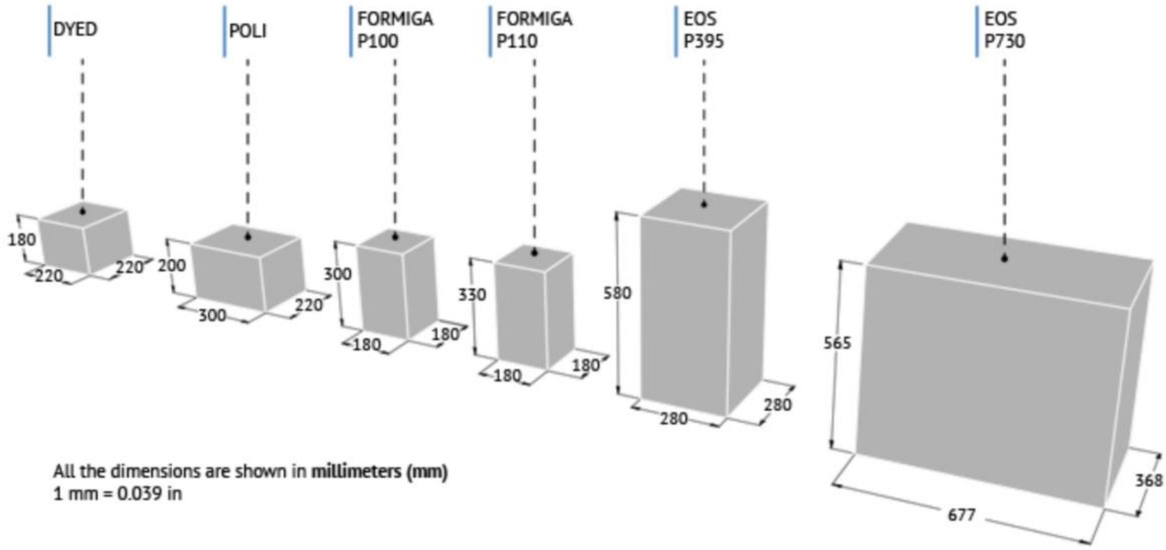


Figure 5.5 Maximum 3D printing sizes for a white plastic polyamide 3D printed object. (Sculpteo2, 2023)

To produce parts that adhere to specific size specifications along with desired strength and functionality aspects using 3D printing technology requires careful consideration of various influential factors like material choices, exact technological requirements and unique component mandates. Incorporating multiple technologies for creating components or combining traditional manufacturing practices through hybrid approaches might become essential at times when certain conditions prevail where standard restrictions do not accommodate desired outcomes regarding part sizes or other technical criteria.

5.2. Accessibility of 3D Plans and STL files

STL files play a crucial role in 3D printing and computer-aided design (CAD). The name STL stands for "stereolithography," which is a widely used 3D printing technology. It is also known as the Standard Triangle Language or Standard Tessellation Language. Each file comprises a series of interconnected triangles that define the surface geometry of a

3D model or object. The number of triangles used and the resulting resolution depend on how complicated the design is. The .stl file extension and lack of colour and texture make STL files easy to recognise.

3D Systems developed the STL file format in 1987 as part of their stereolithography printing technology for commercial 3D printers. This process employed a computer-controlled laser beam and pre-programmed CAD software to create 3D models for rapid prototyping. The STL file format has remained relatively unchanged since its creation and is now considered the standard for 3D printing. It continues to use triangular tessellation to construct the geometric surface of an object, storing information about each triangle, such as the coordinates of its vertices.(STL, 2023)

The STL file format offers several advantages, but also has some limitations that may make it unsuitable for specific applications.

Benefits of STL Files:

1. Universal support: Because almost all 3D printers can use and support the STL file format, it is a dependable choice when it comes to designing and printing 3D models or objects.

2. Versatility: STL files can be used to produce a wide variety of objects, ranging from lamps and plant pots to camera tripods and accessories for drones.

3. Smaller file size and faster processing: In comparison to other formats, STL files are typically smaller in size and process more quickly because they lack colour and texture. For printing objects in a single colour and material, STL is a wise choice.

Disadvantages of STL Files:

1. Limited colour and texture capabilities: While STL is great for printing complicated shapes, it has few options for colour and texture. It is, therefore, primarily used to create prototypes rather than finished products.

2. Lack of metadata storage: Metadata, which is necessary for publishing and includes information like authorship, copyright, and location, cannot be stored in STL files. (Adobe, 2023)

In recent years, 3D printer models and STL files have become more widely available. Many websites offer marketplaces and repositories for both free and paid STL files, serving a variety of purposes and interests. Thingiverse, Cults, Printables, MyMiniFactory, Pinshape, YouMagine, and Ameede are a few of the most well-known platforms.

More than 1.8 million free STL files are available on Thingiverse, the largest content hub for 3D printer models. UltiMaker, a joint company between MakerBot and manages Thingiverse, which offers a sizable selection of 3D printer models from a devoted community of makers.

The French-based platform Cults combines a vibrant community and market for sharing or selling STL files. Cults allow users to follow their favourite designers and receive updates on new creations. It has over 850,000 high-quality 3D printer models, 300,000 of which are free downloads. English, French, Spanish, and German are all supported on the website.

The Prusa Research-founded printables repository, which offers more than 260,000 free STL files compatible with all FDM machines, is quickly expanding. Even pre-sliced G-code for Prusa machines is included with some models.

With over 154,000 3D printer files available, MyMiniFactory, a website well-known for its emphasis on gaming, tabletop role-playing, anime, and geek culture, provides a community space. MyMiniFactory guarantees that its free and paid 3D printer files have undergone quality testing because of its partnership with iMakr, an online retailer of 3D printers and accessories. (3D printing, 2023)

Nevertheless, different files might be unavailable depending on the particular repair component or application. The cost of obtaining the desired files should be considered when determining whether to use 3D printing in a repair shop setting, even though some websites may offer STL files for free.

5.3. Software Options and Applications for 3D Printing

The proper software selection for model creation, editing, and preparation is critical to achieving favourable results in 3D printing projects. With multiple options available in the market that suit beginners and industry professionals- let's delve into some prominent ones- targeting specific use cases:

1. CAD Software - technology such as Computer-Aided Design software empowers individuals to create highly-based three-dimensional models fit for print production purposes. The top CAD software choices are Autodesk Fusion 360, Tinkercad, Sketchup and Rhino. These top-tier programs provide a wide variety of functions, from developing intricate structures to tweaking pre-developed designs. Their user-friendly advantage extends further with easy file export functionality guaranteeing seamless implementation on compatible printers.

2. Slicing Software - Ready-made 3D models are useless without proper conversion tools that translate them into usable instructions. Slicing software fills this gap by converting them into G-code printers that can comprehend efficiently. Industry leaders such as Cura, PrusaSlicer, MatterControl and Simplify3D offer sophisticated features that allow users to tweak their prints according to their needs and preferences. Layer height adjustment options mixed with control over supported structures and other factors enable optimal performance during printing.

3. 3D Scanning Software - With the emergence of powerful 3D scanning software, producing exact digital replicas from original physical objects has become increasingly simple. Programs like Autodesk ReCap, Artec Studio, and Meshroom provide a range of supportive features that aid in converting scan data into dynamic and customisable 3D models - easily editable and printable for any requirement. The application of this technology is most prevalent in producing replacement parts or components with utmost ease.

4. Mesh Repair and Editing Software - turning 3D designs into physical objects via printing is exciting but often difficult if adequate preparation isn't undertaken beforehand. That said, various tools are available for addressing issues related to mesh architecture on digital models. Among them are programs like Meshmixer or Netfabb, which offer features aimed at repairing errors, including holes or overlapping surfaces, while optimising structures before sending them off for printing. By properly leveraging these applications, one can ensure that they'll obtain good outcomes.

5. Simulation and Optimization Software - specialised software programs such as Autodesk Netfabb, nTopology, and Materialise Magics can optimise and simulate 3D models before printing. With these tools, users can examine the printing

process, detect potential problems, and make design adjustments to enhance print quality while decreasing material consumption. (3D printing, 2023)

Ensuring a company has selected appropriate software tools to meet its individual needs is key for improving project results through 3D printing and streamlining processes. Alongside this maintaining a certain level of expertise is required by taking time to experiment with different settings for optimal performance levels and higher-quality output.

5.4. Customisation and enhanced replacement part compatibility

The emergence of 3D printing technology has transformed the landscape of car part fabrication and customisation, offering a range of advantages compared to traditional manufacturing methods. Our focus here is on exploring how the flexibility offered by 3D printing has facilitated the production of bespoke parts that achieve improved vehicle fitment.

1. Personalization - The flexibility afforded by 3D printing technology allows for an impressive degree of customisation in creating replacement parts tailored to specific needs or preferences. Repair shops and private users can leverage this capability to fashion unique solutions that explore novel forms while retaining functionality - accentuating their personal style in the process. From custom emblems boasting uniquely designed insignia to bespoke interior components bearing intricate patterns - leveraging advanced additive manufacturing techniques represent unbeatable boundless opportunities for creativity and innovation.
2. Precise Fitment - The application of 3D printing can guarantee high accuracy and precision in the production of parts, which results in a perfect fit of replacement components with their intended applications hence minimising the necessity for

further alterations or adjustments. Consequently, this streamlines the repair process and enhances both vehicle performance and aesthetics.

3. Complex Geometries - The emergence of 3D printing technology has forever altered how we approach manufacturing by enabling us to produce intricate shapes and structures that were once impossible using traditional procedures. With this innovation comes access to more efficient components designed specifically with performance in mind - lighter-weight materials and cutting-edge cooling systems immediately come to mind as prime examples. Moreover, such complexity permits repair shops and other individual creators opportunities for creative expression; they can now devise novel solutions tailored precisely to their customers' demands.

4. Rapid Iteration - The capability to rapidly alter and adjust designs through 3D printing offers the opportunity for repair shops or individuals to experiment with substitute components until they attain the desired fitting and functionality. This repetitive procedure is more efficient in terms of time and resources than conventional manufacturing methods, which facilitates speedy prototyping and enhancement of ultimate parts.

Although additive manufacturing has been employed for customising cars, it hasn't gained traction yet. Traditional methods of upgrading or replacing vehicle parts tend to be expensive; hence why more people are turning towards 3D printing as a viable solution given its attractiveness in terms of cost-effectiveness without compromising quality. By using this cutting-edge tech, car owners can now produce unique parts ranging from merely cosmetic decorations to fully functional components that align with their specific design standards while enjoying superior structural accuracy coupled with lightweight construction methods - all features that benefit the environment too.

An example of this trend can be found with Ford, which has made 3D files available for customising its Maverick model. Through the "FITS System," Ford allows car owners to 3D print parts that offer eight storage slots for attaching accessories in the central area or under the seats, catering to each user's needs and preferences.

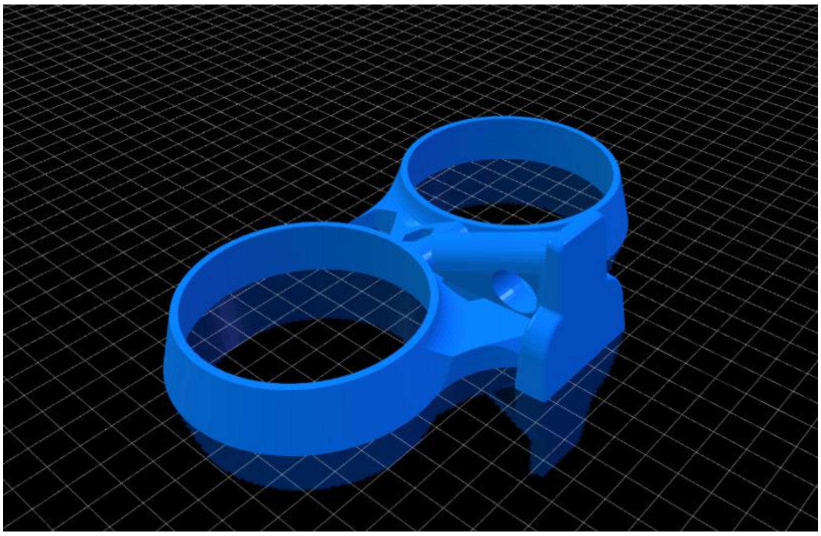


Figure 5.6 Ford Maverick Cup Holder 3D model. (Thingiverse2, 2023)

Figure 5.7 Ford Maverick 3D printed cupholder in use. (The Verge, 2023)

Peugeot, which offers options for customising vehicles with 3D-printed accessories that are pleasant to the touch, lightweight, and simple to use, is also utilising this strategy. The Peugeot Lifestyle store is where these add-ons can be purchased. This store conducts research on customer requirements and strives to make their automobiles as comfortable as is humanly possible through the application of 3D technology. While I was working on this master's thesis, there was only one product that could be purchased, and it was a glasses holder. The new HP Multi Jet Fusion (MJF) 3D printing technology made it possible to print it, so it was not only useful but additionally made to the customer's demands. However, it is currently compatible with the automatic transmission versions of the Peugeot 308 and 408. The item's STL model can be purchased for a total cost of 80 euros. (Stellantis, 2023)

Figure 5.8 Peogeot 3D printed glasses holder. (Peugeot Lifestyle, 2023)

By leveraging the power of 3D printing, car manufacturers like Ford and Peugeot are pioneering new ways for customers to personalise and adapt their vehicles. As more companies consider this technology, drivers will have even more affordable and sustainable customisation options.

6. THREE-DIMENSIONAL PRINTING IN THE AUTOMOTIVE INDUSTRY

6.1. Current adoption status of 3D printing in the automotive industry

The automotive industry has embraced 3D printing technology to drive innovation and optimise manufacturing processes. Of all available options, Fused Filament Fabrication (FFF) is currently one of the most widely used types of 3D printing in this sector due to its ability to work with materials possessing properties similar to plastic. This technology allows car makers to maintain production continuity and become less dependent on third-party vendors while streamlining their operations.

Although additive manufacturing was previously used almost exclusively for rapid prototyping within auto manufacturing has been a growing shift towards using it for creating final car parts, according to SmartTech Publishing reports. The automotive 3D printing market is expected to generate as much as $9 billion by 2029, with industry leaders like Volkswagen, BMW and Ford driving this trend forward with force.

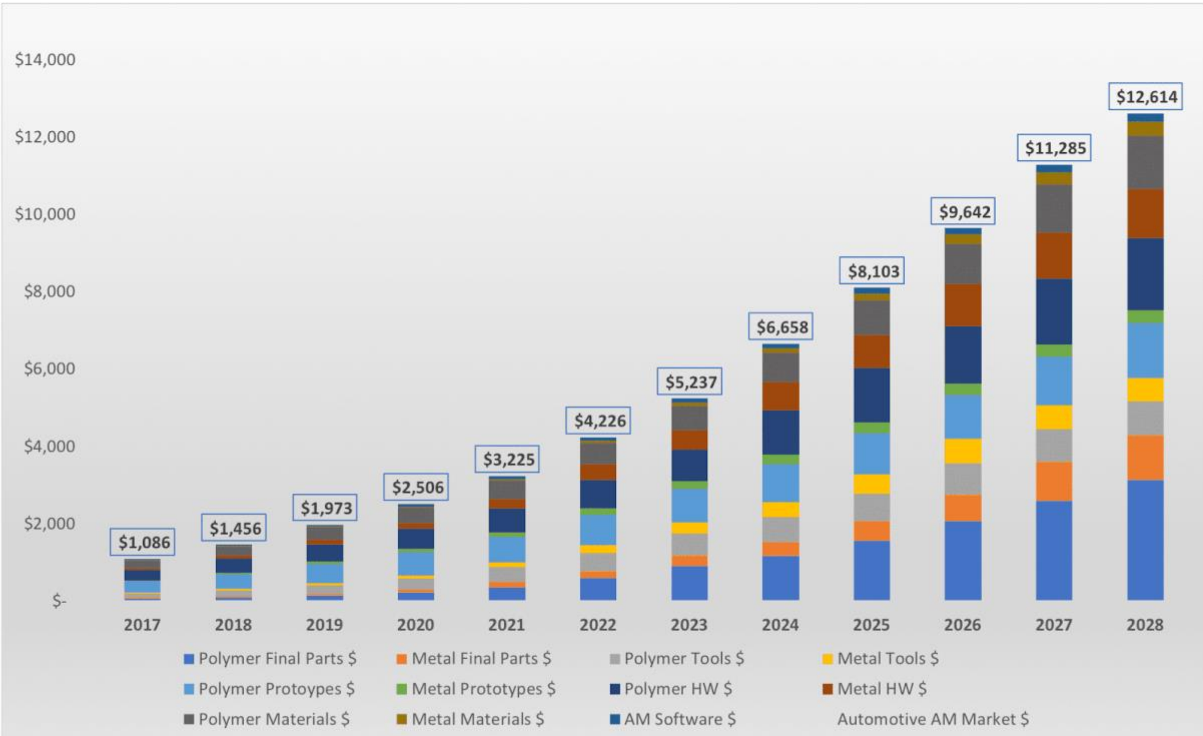


Figure 6.1 The automotive additive manufacturing market in 10 years (2017-2028). (SmarTech Analysis, 2023)

According to SmarTech Analysis (published in 2016), the overall market for additive manufacturing in the automotive sector is expected to reach $5.3 billion in revenues by 2023 and grow to an impressive $12.4 billion by 2028. This rapid adoption of additive manufacturing for production purposes is considered a turning point for the industry. While prototyping and tooling remain important applications, parts production is predicted to become the primary revenue opportunity by the end of the forecast period, surpassing all other segments. (SmarTech Analysis, 2023)

This shift towards parts production includes metal and polymer parts produced both internally by automotive OEMs and through outsourcing. By the end of the forecast period, parts production is expected to account for nearly $4.3 billion in revenue, driving significant growth in the automotive additive manufacturing segment. This ongoing transformation showcases the immense potential and evolving role of 3D printing in shaping the future of the automotive industry.

In the car sector, the drive for continuous performance improvements in vehicles frequently results in a demand for the development of one-of-a-kind, complicated component parts. Using 3D printing, it is possible to design and fabricate parts that are tailored to a specific driver or vehicle.

Due to the low demand, the German manufacturer of luxury cars, Porsche, decided that it was not in the company's best interest to continue producing and storing spare parts for its classic cars. Porsche is now using 3D printing for metal and plastic parts, and it has also added a digital inventory of spare parts to its catalogue to meet the unpredictability of customer demands better. This helps to keep classic cars on the road, which keeps the owners of classic cars loyal and content. (Markforged, 2023)

In 2018, a Hong Kong-based startup named XEV Limited announced the development of a new electric car model, the LSEV, which would feature fewer than 100 parts compared to the thousands found in a Tesla. The two-seater LSEV takes only three days to manufacture, thanks to the utilisation of 3D printing technology.

Figure 6.2 3D printed car LSEV. (SCMP, 2023)

In terms of size, the LSEV is similar to a Smart car with measurements including a height of 1.5 meters, length of 2.5 meters, and width of 1.3 meters. Despite its small frame, the vehicle weighs a mere 450 kg while showing impressive capabilities such as reaching speeds up to 70 km/h and travelling up to an impressive range of about 150 km (93 miles) once fully charged up on energy supply. The LSEV is predominantly comprised using three kinds of materials which are enhanced nylon in combination with polylactic acid - both being common materials currently used for producing items through the additive manufacturing process - along with TPU that adds elasticity to its overall structure design. All metal-based components constituting the engine room and chassis are generated using conventional manufacturing processes.

XEV was united by approximately fifty experts who helped build this innovative electric-powered vehicle from scratch, along with designing specialised equipment like customised printers exclusively tailored for printing desired components required specifically for project use. (Interesting Engineering, 2023)

An inspiring example of the capabilities of 3D printing in the automotive world is the story of Sterling Backus, a physicist and father who managed to 3D print an entire Lamborghini Aventador. Sterling began by downloading a 1:10 scale model of the Aventador, scaling it up, separating the parts, and adding his own custom modifications, such as widening the car's body.

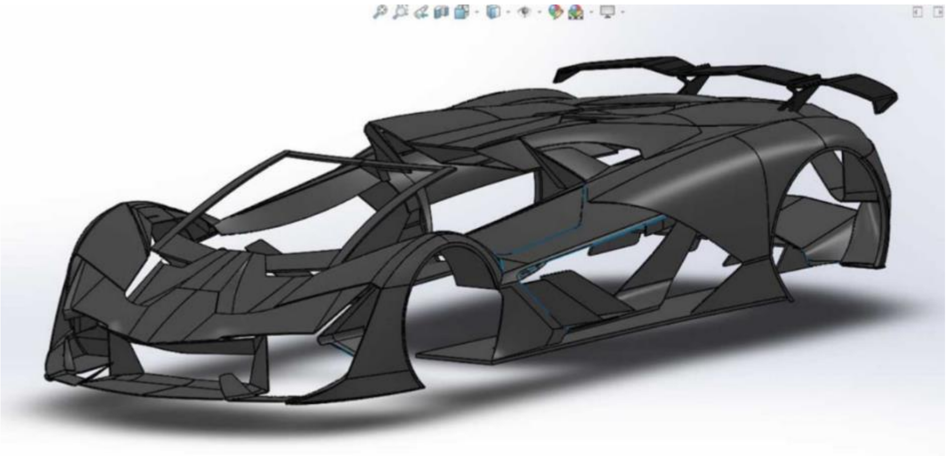


Figure 6.3 3D CAD file for Lamborghini Aventador. (Wong, 2019)

Sterling used a Creality Cr 10S, a basic 350USD printer designed for hobby projects, to 3D print the entire car. The printer was pushed to its limits, running continuously for 15 months before eventually giving out, but by then, Sterling had printed the entire outer body. The Cr 10S prints with standard PLA filament, which is suitable for small toys but not for large supercars, as it has a glass transition temperature of 50-60°C. At these temperatures, PLA starts to soften and warp, posing a problem in outdoor conditions and with the V12 engine: enhanced nylon in combination with polylactic acid - both motive industry, not just for manufacturing individual parts but even for creating an entire car, with significant time and effort.

Ford's continued commitment to integrating 3D printing into its product development cycle. During the design process for the Shelby GT500, Ford's engineering team used virtual testing to analyze over 500 cooling and aerodynamic 3D designs. They then 3D printed and tested prototypes, such as front splitter wickers, to evaluate their performance. Notably, the 2020 Shelby GT500 also features two structural 3D-printed brake components, created using Carbon's Digital Light Synthesis (DLS) technology and EPX (epoxy) 82 material. These components have passed all of Ford's performance standards and requirements.

Figure 6.4 Carbon 3D printed Ford HVAC lever arm. (TCT Magazine, 2023)

This use of 3D printing in both the design process and for manufacturing components highlights Ford's commitment to exploring the potential of additive manufacturing in the automotive industry. (AMFG, 2023)

In addition to its famous car bodies, the British automaker Bentley is well known for its plans to broaden the uses of 3D printing in the automotive industry. The company produced more than 15 000 components in 3D in 2021 thanks to an investment of more than 3 million euros, which reduced waste and speeded up design and manufacturing. Bentley derives significant process and financial benefits from the use of additive manufacturing, and its customers also benefit greatly. For instance, they can order unique and customised components thanks to 3D printing. (3D Natives, 2023)

6.2. Materials commonly used for 3D printing automotive components

In the world of automobiles opting for the appropriate material is imperative to ensure the robustness, practicality, and proficiency of printed components through 3D printing. This section intends to shed light on some of the widely utilised materials in 3D printing automotive parts:

1. ABS (Acrylonitrile Butadiene Styrene) - ABS is a popular material for 3D printing automotive components due to its strength, durability, and resistance to heat and impact. It is often used for creating interior components, such as dashboard elements, door handles, and various trim pieces.

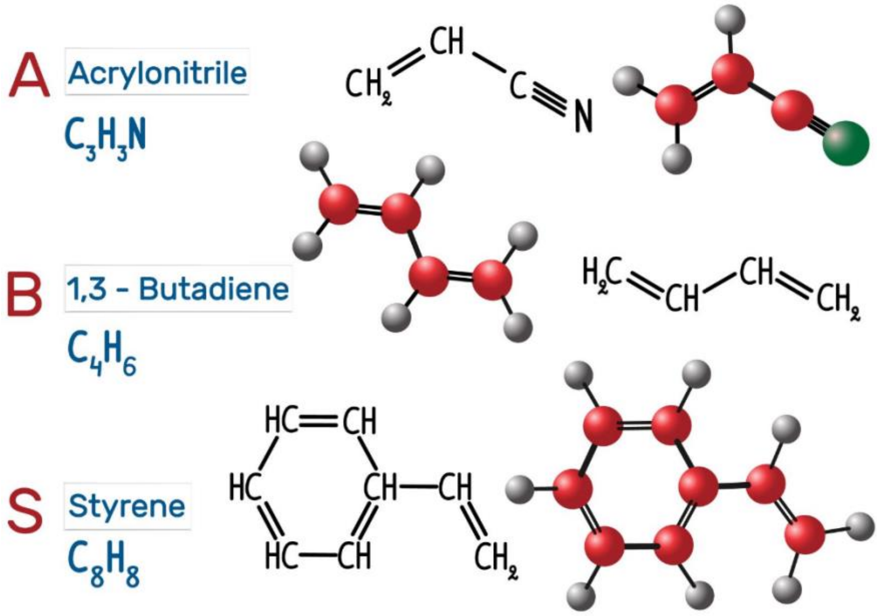


Figure 6.5 Chemical structure of ABS (Acrylonitrile Butadiene Styrene). (BPF, 2023)

2. PLA (Polylactic Acid) - is an environmentally friendly, biodegradable thermoplastic made from renewable resources like cornstarch. While not as strong or heat resistant as ABS, PLA is an excellent option for lightweight, non-load-bearing parts and also decorative components.

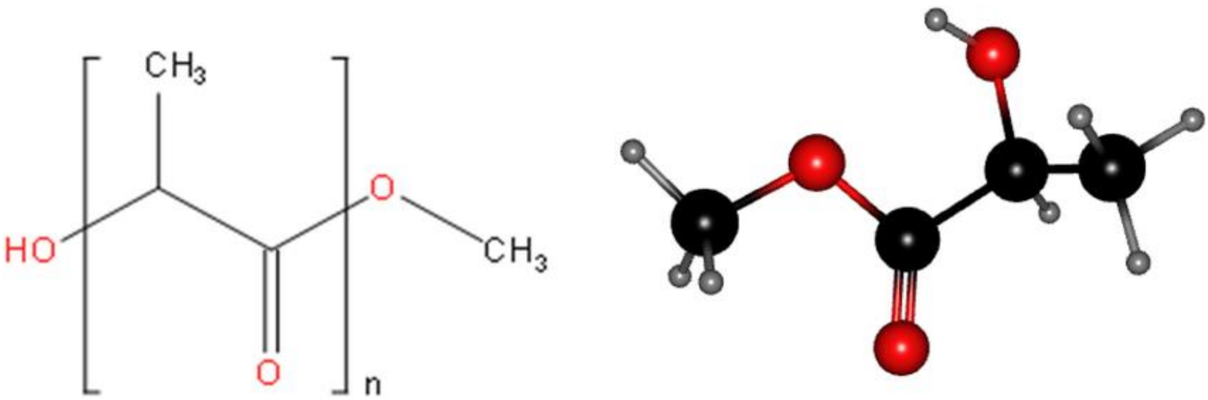


Figure 6.6 Chemical structure of PLA (Polylactic Acid). (ResearchGate, 2023)

3. Nylon (Polyamide) - In numerous industries where dependability is key – from industrial machinery manufacturing through consumer retail goods production – nylon stands out as one of the best possible candidates for any resilient component or part. The incredible blend of features nylon provides - being lightweight yet immensely strong, offering a great degree of flexibility while simultaneously withstanding wear &

tear- make it a go-to option when designing anything from gears & bearings through to external parts capable of handling impacts effectively.

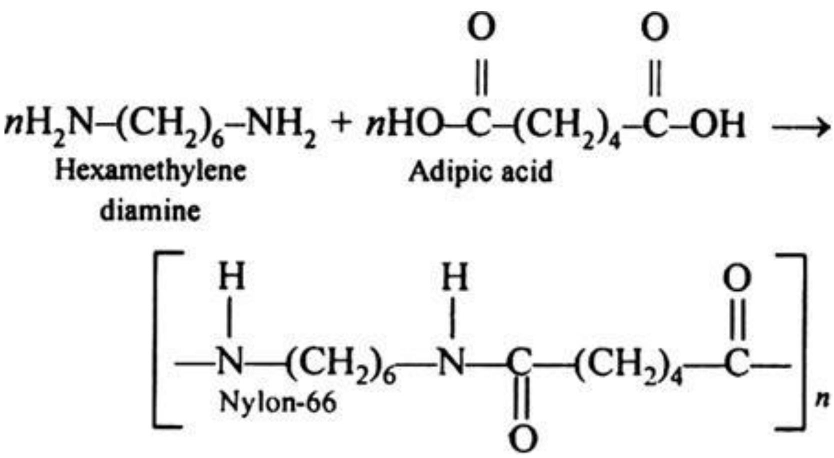


Figure 6.7 Chemical structure of Nylon (Polyamide). (Chemical Book, 2023)

4. PETG (Polyethylene Terephthalate Glycol) - PETG's flexibility lies in its ability to blend strength and durability- typical traits of ABS- with the easy-to-print properties and ecological compatibility found in PLA. Its outstanding resistance against chemical substances, UV light exposure as well as moisture means that it can effortlessly be adapted for use in different auto applications both indoors and out.

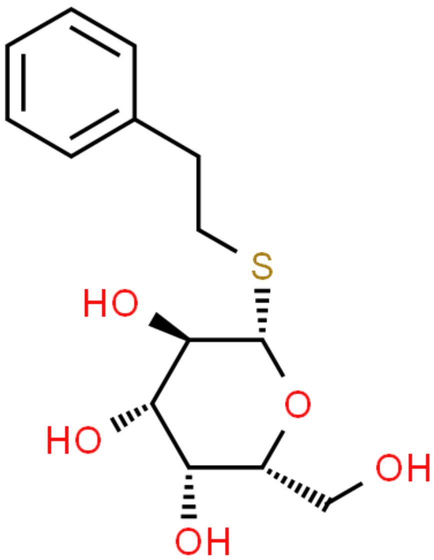


Figure 6.8 Chemical structure of PETG (Polyethylene Terephthalate Glycol). (ChemSpider, 2023)

5. Carbon Fiber - To manufacture strong and durable parts capable of withstanding high-stress situations and extreme temperatures using 3D printing technology, it is possible

to use filaments reinforced with carbon fibre. This combination produces lightweight structural parts like suspension components, brackets, or mounts that have superior strength properties when compared to traditional manufacturing processes.

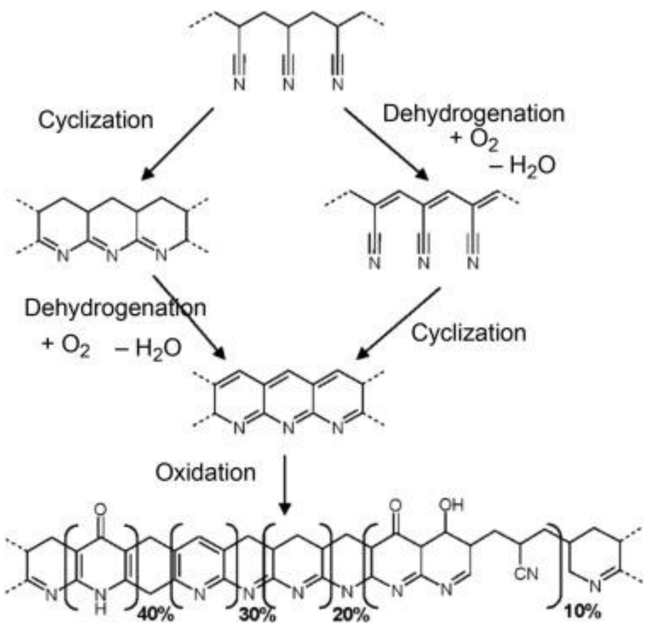


Figure 6.9 Chemical transformations of polyacrylonitrile before its transformation into carbon fiber: cyclization, dehydrogenation, and oxidation. (Bajaj, Roopanwal, 1997)

6. Metal Alloys - With technological advancements in metal 3D printing, automakers now use it extensively to produce auto parts with challenging geometries and high strength-to-weight ratios. The choice of materials typically includes stainless steel and aluminium as they offer excellent performance across applications such as engine components or chassis parts; however, sometimes manufacturers use titanium's unique features for specific requirements. Overall this innovation offers new possibilities for designing safer and more efficient vehicles while reducing weight without sacrificing performance or safety standards. (Dipak, Trupti, 2022)

To ensure the highest efficiency, durability, and cost-effectiveness, it is essential for automotive manufacturers and designers to consider the specific requirements of each part. Combined with the proper 3D printing technology, these materials can significantly improve production efficiency, product flexibility, and overall product quality.

The integration of 3D printing has a significant positive impact on production support, which consists of the equipment and infrastructure used to sustain the manufacturing process. Multiple departments and disciplines, including assembly, quality control, health and safety, and possibly more, can produce and utilise tools more efficiently thanks to this technology.

In addition, 3D printing provides a quick and cost-effective method for creating substitute parts. When genuine parts are not yet available for tooling setup verification during new model-year production line changes, these parts serve as temporary replacements. Long before final parts and assemblies are available, this method can significantly reduce the time required for tooling validation and rapidly identify any necessary adjustments.

6.3. A variety of 3D printers for the automobile industry

The automotive industry has at its disposal several diverse types of 3D printers that come with unique functionalities suited for specific tasks providing various benefits dependent upon their technology design. Choosing the appropriate one among these options requires careful consideration based on factors like financial constraints, geographical location material choice or project timelines, among many other relevant considerations concerning particular applications designed by businesses in this sector aimed at optimising their processes, improving product quality and remaining competitive against peers within this industry space.

Budget is another essential factor to consider - 3D printers can range in price from less than $200 to more than $2 million. (Parker, 2023)

Although cheaper printers may be suitable for hobbyists, professional printers for business applications typically begin at $3,000. However, a budget of at least $5,000 provides greater flexibility and options when purchasing a printer. It is essential to calculate both direct and hidden costs associated with 3D printing, including

Direct Costs:

- 3D Printer Price
- Labor Costs
- Equipment
- Materials

Hidden Costs:

- Consumables
- Electricity costs
- Training & Electrical Resources
- Machine operator
- Slicing Software

In addition, it is crucial to consider ISO certification when choosing a 3D printer. For example, Raise3D's factory is ISO-certified, indicating that their products are manufactured in factories with ISO9001 and ISO14001 accreditations. These certifications guarantee that the printers are manufactured with high-quality components and follow rigorous quality and environmental management standards.

Considering the factors mentioned above, the author has created the following selection of 3D printers that represent some of the most popular and dependable options for automotive applications:

- Stratasys Fortus 450mc - is a versatile and durable FDM printer that is renowned for its dependability and ability to print with a wide variety of engineering-grade thermoplastics. Its large build volume and high resolution make it ideal for producing functional prototypes, end-use parts, and manufacturing tools for the automotive industry. Average price 185 000USD (TreatStock, 2023).

Figure 6.10 Stratasys Fortus 450mc 3D Printer. (StrataSys, 2023)

- Carbon M2 - utilises Digital Light Synthesis (DLS) technology to produce high-resolution, isotropic, smooth-surfaced parts with exceptional mechanical properties. This printer is suitable for manufacturing intricate automotive components that require a combination of strength, durability, and accuracy. The Carbon M2 is a subscription-based model costing 25 000 USD per year.

Figure 6.11 Cabon M2 3D printer. (Carbon, 2023)

- HP Multi Jet Fusion 5200 - is an industrial-grade 3D printer that employs Multi Jet Fusion (MJF) technology to produce high-quality, intricate parts rapidly. It provides production flexibility and scalability for automotive parts made from various materials, such as PA 11, PA 12, and TPU, making it ideal for manufacturing. The cost of the 5200 machines is between 350,000 USD and $500,000 USD. (MasterGraphics, 2023)

Figure 6.12 HP Multi Jet Fusion 5200 3D printer. (Formadditive, 2023)

- EOS P 770 - is a large-scale, high-performance SLS printer intended for producing high-quality, complex parts in a wide range of materials, including plastics and metals. Its advanced laser system and thermal management capabilities make it a popular choice for producing automotive components requiring precision, durability, and strength. A brand new model can be purchased with the starting price of 800 000 USD, a used model is sold with a 585 000 USD price tag. (CNC Machines, 2023)

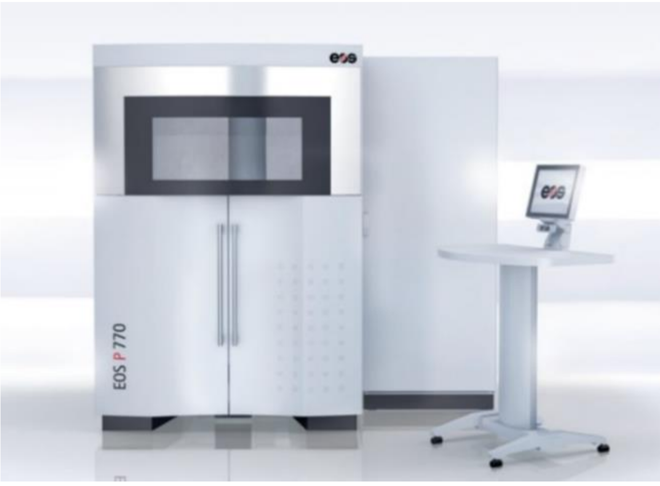


Figure 6.13 EOS P 770 3D printer. (3DDT, 2023)

- Desktop Metal Studio System - is an office-friendly metal 3D printer that uses Bound Metal Deposition (BMD) technology to produce high-quality metal components with intricate geometries. Its usability and compatibility with various metal alloys make it a viable option for the in-house production of automotive components and tooling. Initially priced at 120 000 USD. (All3DP2, 2023)

Figure 6.14 Desktop Metal Studio System 3D printer. (Aniwaa, 2023)

To sum up the discussion on selecting the appropriate 3D printer for automotive applications company must possess a comprehensive awareness of the essential materials to be used alongside budgetary constraints and unique application-specific requisites. By considering these crucial aspects during decision-making processes, businesses can gain valuable insight towards acquiring an ideal 3D printer that meets their individual requirements whilst enhancing performance efficiency and durability as well as being cost-effective during manufacturing operations.

6.4. Real-world comparison of 3D-printed versus conventionally sourced components

As the technology advances, the question arises: can 3D printing replace traditional manufacturing processes or complement them to create more efficient and cost-effective solutions? To analyse this, we will examine on one item, focusing on its production, cost, and overall effectiveness.

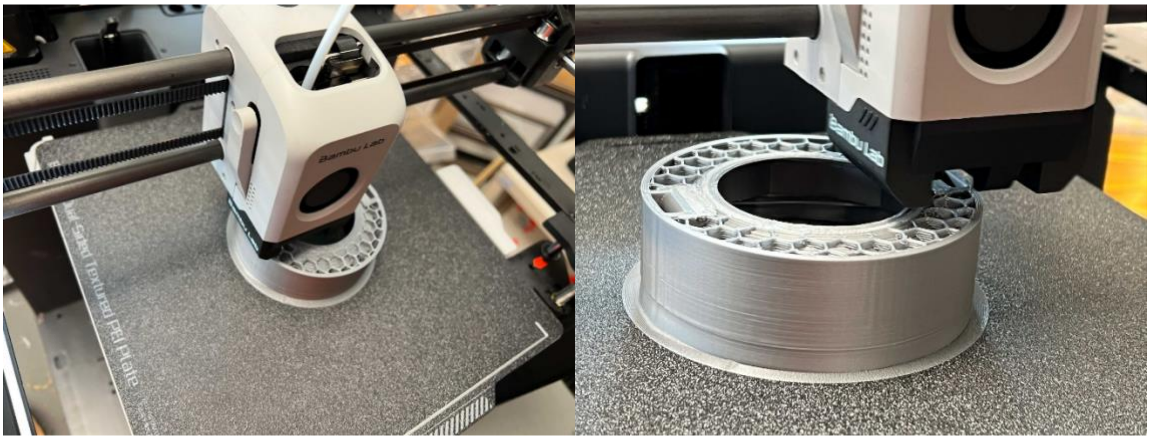
The item is not a car part itself but a commonly used tool in repair shops an oil filter wrench. Oil filter wrenches, in combination with oil filter sockets, simplify the process of changing oil and fuel filters on various vehicle makes and models. Each socket typically features a black phosphate protective coating to guard against rust and corrosion. They come in different sizes, such as 24mm, 27mm, 29mm, 32mm, and 36mm, and are compatible with various vehicle manufacturers. These wrenches are widely available through online retailers like Amazon, eBay, and Aliexpress, with designs and shapes varying depending on the manufacturer.

For this comparison, the author has chosen an oil filter wrench with a black phosphate protective coating and sizes from 65mm to 100mm. The author will investigate the production process, costs, and other factors for both 3D printed and conventionally sourced oil filter wrenches to determine the potential benefits and limitations when 3D printing.

Figure 6.15 Oil filter wrench set and wrenches. Pictures by Author

Figure 6.16 Oil filter wrench set and wrenches. Pictures by Author

In this case the author examined the 3D printing of an oil filter wrench that he had 3D printed.



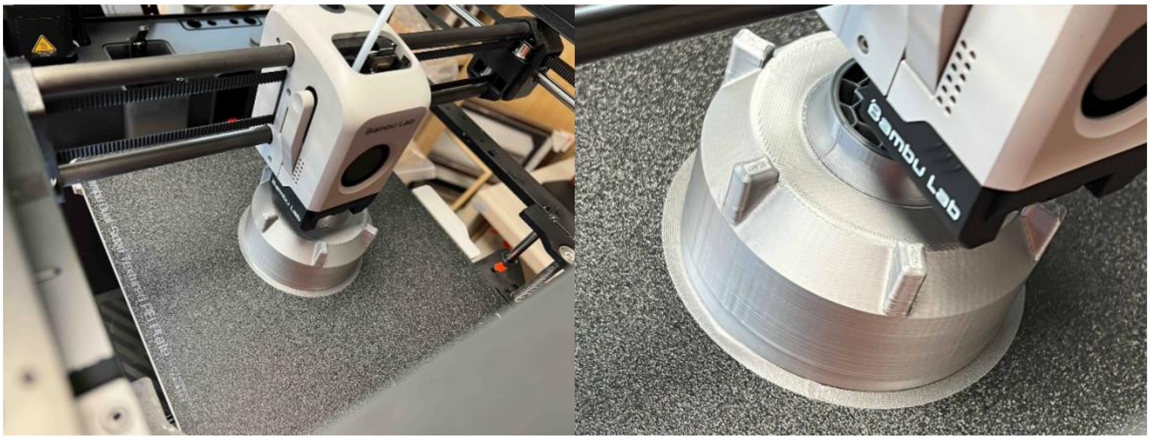


Figure 6.17 Oil filter wrench 3D printing process. Pictures by Author

The oil filter wrench measured 90mm in size and was printed using a Bambulab P1P 3D printer. The chosen material for this print was PLA+ due to its durability and ease of printing. The design was created using Bambu Studio, a software program specifically designed for 3D printing projects with Bambulab printers.

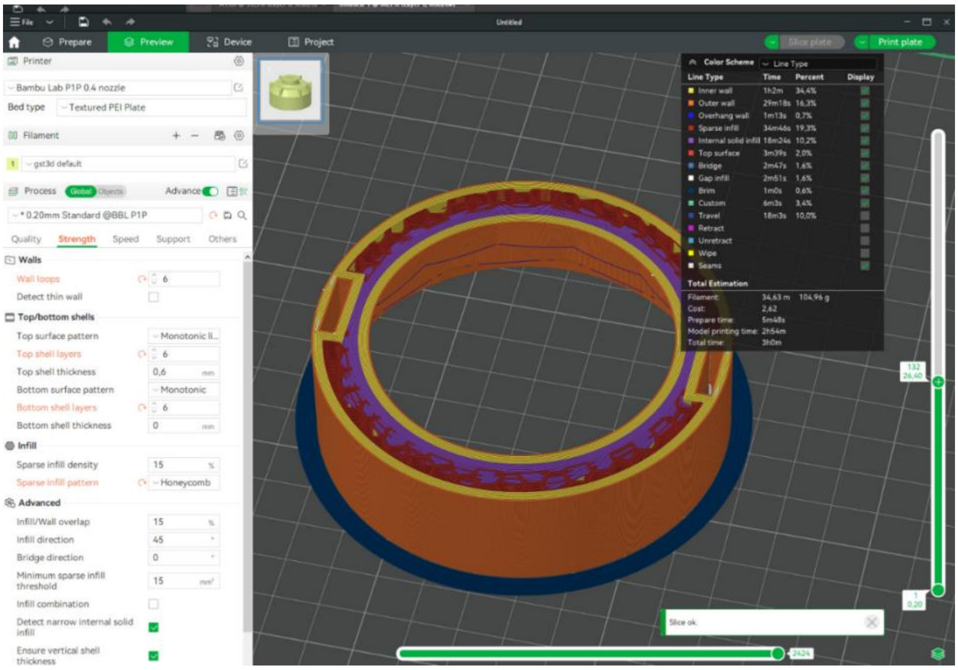


Figure 6.18 Oil filter wrench 3D model processing with Bambu Studio software. Auhor's screenshot.

The printing process took 3 hours to complete, consuming 34.63 meters of filament in the process. The print settings included six wall loops and a 15% infill, with a honeycomb infill structure to ensure the wrench's solidity and durability. The final weight of the 3D-printed oil filter wrench was 104.96 grams.

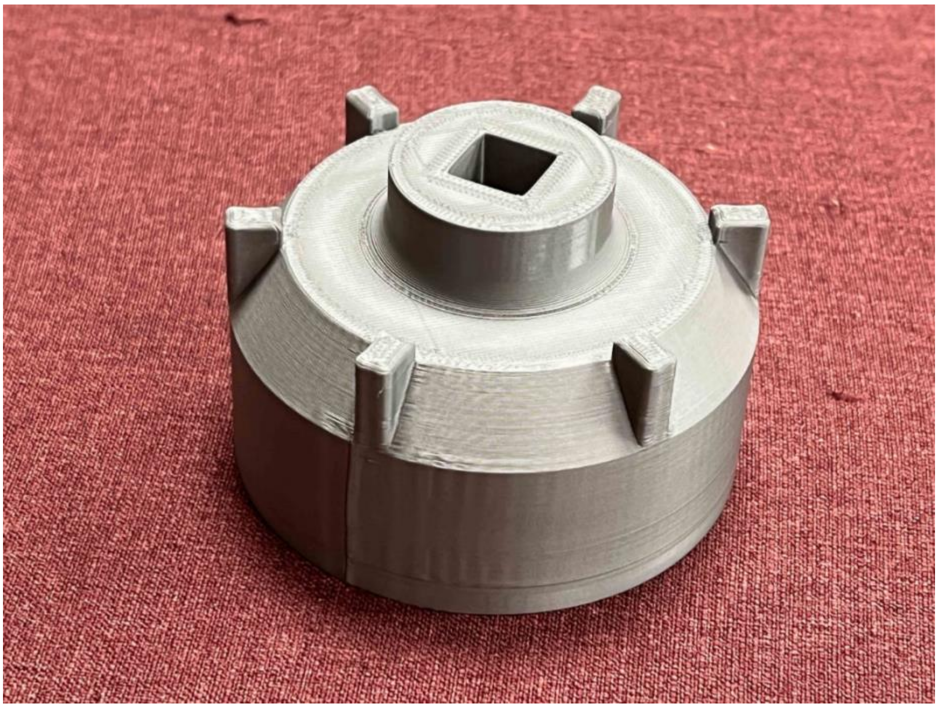


Figure 6.19 Completed 3D printed oil filter wrench (90mm). Picture by Author

The cost of producing this 3D-printed oil filter wrench was 2.62 euros, taking into account the filament consumption and the price of the filament. The PLA+ filament used for this project costs 25 euros per kilogram, making it an affordable option for producing durable, high-quality 3D printed tools for automotive repair shops.

In conclusion, the metal oil filter wrench set, which includes 14 different sizes, is priced at 30 euros. On the other hand, 3D printing an individual wrench using a plastic printer costs 2.62 euros per size. It is important to consider the differences in material and printer costs, as well as potential waste when deciding between purchasing a complete set or printing each size individually.

The example wrench set is made of metal, while the 3D printed version is made of plastic. Metal 3D printers and their materials are significantly more expensive than plastic 3D printers. Metal printer costs range between $50,000 to $1 million, while plastic printer costs range from $600 to $4,000. (PolySpectra, 2021)

Although plastic 3D printers have higher material usage and wastage compared to metal 3D printing, the lower upfront costs might still make them a more attractive option for some repair shops. However, it is worth noting that the lower material wastage in metal

3D printing could make the higher initial investment justifiable in the long term. Additionally, a failed print in metal 3D printing can cost hundreds or thousands of euros in material costs alone, and unfused metal powders may need to be recyclable, adding to waste streams and wasted material costs. Lastly, it is crucial to consider the skills and knowledge required to operate 3D printing technology. In cases where the repair shop lacks expertise in 3D printing, it might be wiser to purchase the wrench set from a local supplier. Ultimately, the decision should be based on the shop's requirements, frequency of use, budget considerations, and technical expertise.

7. CAR REPAIR INDUSTRY DIFFICULTIES AND LIMITATIONS OF 3D PRINTING

7.1 Interviews with owners of repair shops

To gain a deeper understanding of the needs and perspectives of repair shops regarding the implementation of 3D printing, the author conducted interviews with employees from different repair shops in Tallinn. The author prepared following questions:

- Have you heard about 3D printing?
- What are your thoughts about it?
- How do you feel about implementing 3D printing in your repair work?
- What are the main concerns regarding 3D printing?
- What are your thoughts regarding being more sustainable via 3D printing vs traditional sourcing?
- What are your thoughts towards the future? Will 3D printing be commonly used in the repair industry?

One of the interviewees was Madis Peri, a co-owner of GT Autoteenindus. The interview was executed in person.

Madis demonstrated an understanding of how 3D printing could benefit his automotive repair business during our interview. However, investment expenses regarding obtaining 3D printing equipment prevented him from adopting this technology at present. According to Madis, he could get the most commonly ordered car parts from local suppliers within an hour or less. Not only are these parts affordable but they are also readily available to both himself and customers alike which renders investment into 3D printing within the next 2-4 years unfeasible at present time because of several issues: diverse material requirements necessary for various car models means additional costs; space restrictions related to printers and computer equipment; increased efforts needed when sourcing drawings and software; Lastly, there is concern over needing someone skilled in operating a printer which will further add unnecessary expenditures. To sum up, Madis sheds light on the obstacles confronted by repair shop proprietors when assessing the incorporation of 3D printing technology. While mass-produced parts are easier and cheaper to order, the expenses involved in investing in

3D printing machinery and handling potential logistical complications have compelled him to stick with conventional sourcing practices for the time being.

Madis mentioned an interesting case where a friend of his successfully utilised 3D printing for automotive repair. His friend owned an old car for which parts were no longer being manufactured. To find a suitable replacement for fixing the windshield with a clip, his friend searched online and located a design file for the needed part. He then enlisted the help of a professional who specialised in 3D scanning to create an accurate digital model.

Figure 7.1 Seat Ibiza 1991a. Picture by Author

Once the digital model was prepared, it was used as input for the 3D printer, and the part was successfully printed. Despite the time-consuming process involved in sourcing the design, preparing the digital model, and 3D printing the part, Madis's friend was highly satisfied with the outcome. The 3D-printed part met his needs, and it was a solution he could not have found through traditional part-sourcing methods.

Figure 7.2 3D printed Seat Ibiza windshield clip. Picture by owner of the car

This example highlights the potential of 3D printing technology in addressing specific challenges in the automotive repair industry, particularly for older or rare vehicles with hard-to-find replacement parts. However, it also underscores the need for investing in equipment, software, and expertise, which may not yet be practical for all repair shops.

The second interview was conducted with Ilmar Pukk, owner of Fleet Veod, a logistics company that handles the repair work for its own trucks and machines. The interview took place via a Zoom call. Ilmar was familiar with 3D printing technology and had even experimented with it personally. He described his experiences as a fun hobby and learning opportunity but did not see it as a full-time replacement for his repair shop.

Ilmar expressed reluctance to invest in and implement 3D printing technology for his repair shop, citing the ease of acquiring parts from current suppliers and concerns over the quality and reliability of 3D printed components. He acknowledged that sustainability was a significant concern, particularly regarding the waste generated by packaging materials for parts ordered from suppliers. However, he pointed out that 3D printers and their materials also came with packaging which is also waste, indicating that this issue was not exclusive to traditional part-sourcing methods.

One of Ilmar's primary concerns with adopting 3D printing technology was the lack of knowledge about the required software, programs, and technical processes. He asked where to find accurate and reliable design files, whether they would be free or require additional investment, and how to navigate the various software options.

In conclusion, Ilmar recognised the potential of 3D printing technology for the automotive repair industry and acknowledged its ability to impact the future of repair shops. However, he preferred to wait and observe the development of the technology before considering its adoption, given the current challenges and uncertainties he faced.

The third interview was conducted with Romet Troost via a telephone call. Romet is the co-owner of Camper Help, a repair shop specialising in caravans. He expressed familiarity with 3D printing technology and its potential but admitted to having no personal experience with it. He has heard about companies occasionally offering 3D printing services to repair shops, but he has not seen any tangible products or competitors utilising the technology.

Given his repair shop's niche focus on caravans, Romet does not envision adopting 3D printing technology within the next five years. He explained his reservations, stating, "I just don't trust the quality of the materials, and I don't have enough knowledge to start 3D printing. If a company would offer such a service, I would definitely consider using them, but it all comes down to the final price of the parts I need and whether a customer is willing to pay that price or not."

Regarding sustainability, Romet admitted he had not considered the environmental impact of traditional part ordering and packaging. He acknowledged the importance of reducing waste but pointed out that when parts are ordered from third-party suppliers or manufacturers, they come pre-packaged, leaving him with limited control over waste generation.

Romet remains sceptical about 3D printing, particularly regarding the quality of printed parts. However, he expressed willingness to try free product samples if they were offered to him. He is not actively seeking out 3D printing companies, either domestically or internationally.

In conclusion, Romet sees the 3D printing industry as interesting but believes it needs more time to develop and mature. He compared it to the evolution of mobile phones: "They were big and clumsy in the beginning but look at them now. We can't live without them. They have improved so much. This is exactly what I'm hoping for from the 3D printing industry. It just takes time."

7.2 Evaluation of responses to questionnaires from repair shop employees

To gain valuable insights into the practicality and effectiveness of 3D-printed automotive parts, the author conducted a questionnaire targeted at repair shop workers. This survey consisted of 10 questions and was distributed through a Facebook group dedicated to professionals in the automotive repair industry. The author rewarded five randomly selected participants to encourage participation, ensuring that respondents were motivated to provide honest opinions.

The author collected a total of 28 responses, which provided somewhat first-hand information on the experiences and perspectives of repair shop workers who regularly deal with automotive parts. Through this evaluation, we aim to paint a clearer picture of the practical implications of 3D printing technology in real parts that come pre-packaged when ordered from third-party suppliers or manufacturers.

The findings of the survey are as follows:

1. By and large almost half (i.e. 46.4%) of those who participated in this study stated that they had gained a relatively modest level of expertise - ranging from just one year up to five years' worth - within the automotive repair sector. On top of that, an impressive portion (25%), presumably comprising seasoned professionals with significant know-how and skill sets, revealed they held at least fifteen years' worth of practice under their belt.

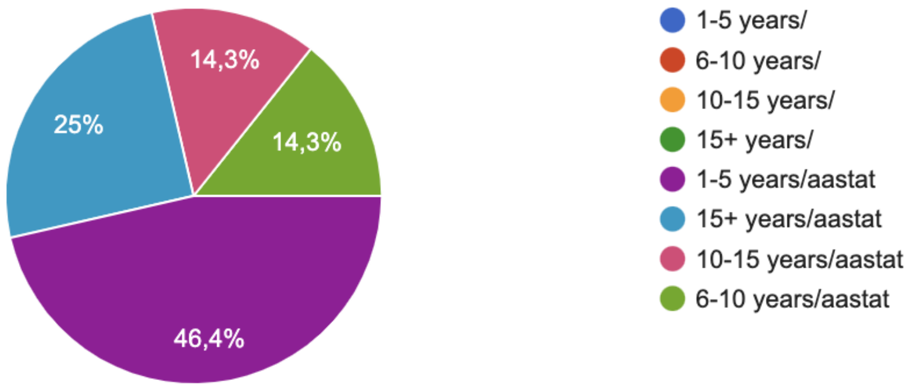


Figure 7.3 Results for question: How long have you been working in the automotive repair industry?

2. As per survey results, passenger cars appeared to be the top priority for repair shops, with 92.2% of establishments offering these services primarily. Behind that were classic or retro vehicles (28%), followed by light trucks (32%).

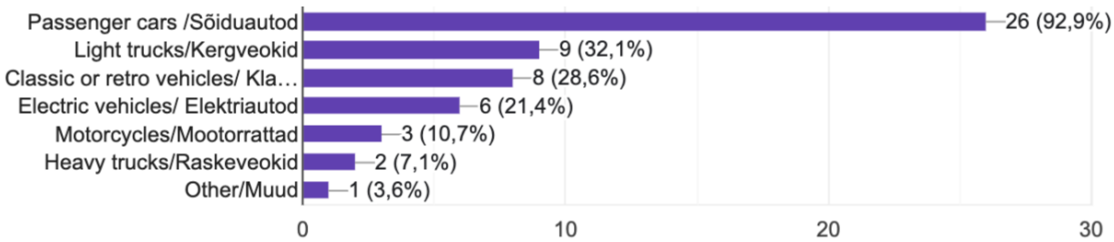


Figure 7.4 Results for question: What types of vehicles does your repair shop primarily service?

3. It was revealed that sourcing replacement parts proved troublesome for around half of the participants at times. Notably, however, more than one-third (35.7%) indicated seldom experiencing such challenges.

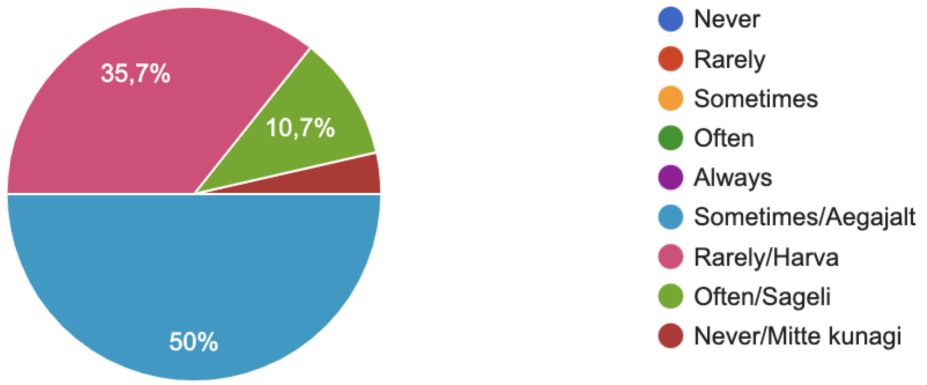


Figure 7.5 Results for question: How often do you face difficulties in sourcing replacement parts for the vehicles you service?

4. Procuring replacement parts can often be fraught with obstacles such as interminable lead times, insufficient stock supply and sub-par product quality – difficulties that recent data collected by industry experts bear out: a staggering majority of buyers - or exactly 64% - reported long wait times as their main challenge; a close second was inadequate availability affecting no less than 60% of those surveyed; followed closely by poor quality ratings given by more than half - of precisely - 57% - of all purchasers interviewed on this issue alone.

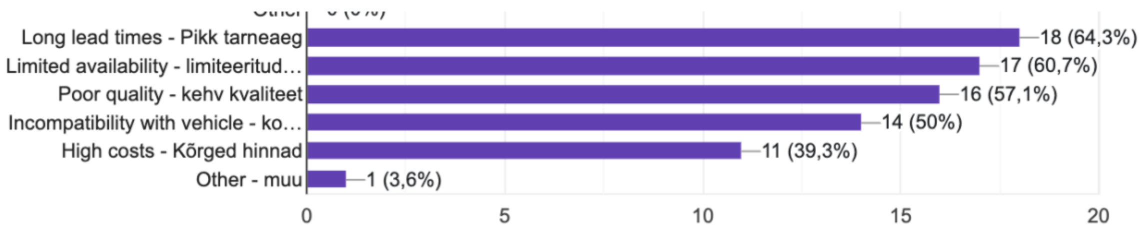


Figure 7.6 Results for question: What challenges do you typically encounter when sourcing replacement parts?

5. Nearly 70% reported that they had contemplated employing 3D printing technology for automotive repairs at their respective establishments.

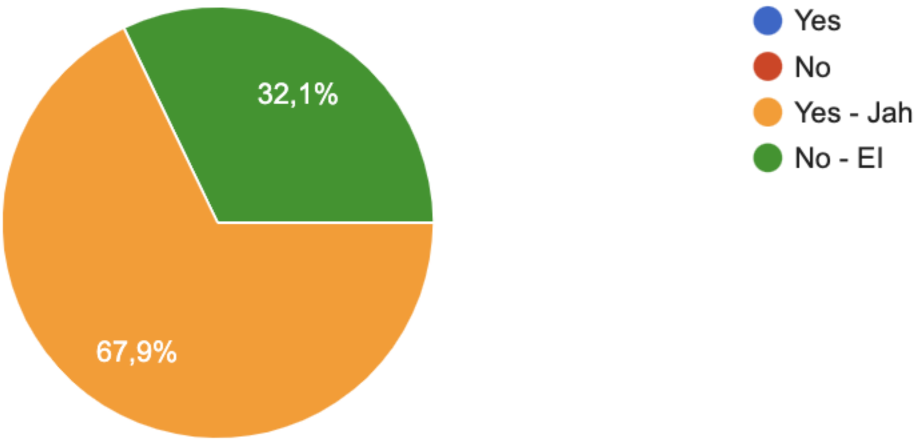


Figure 7.7 Results for question: Have you ever considered using 3D printing technology for automotive repairs at your repair shop?

6. The most significant potential advantage of utilising 3D printing is the enhancement of repair capabilities for older or rare vehicles, with a percentage of 76.9%.

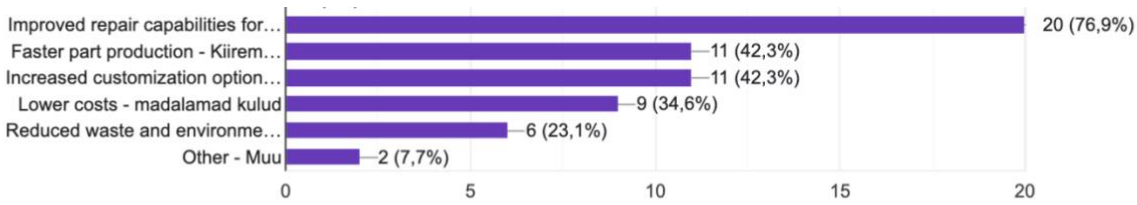


Figure 7.8 Results for question: If you have considered using 3D printing, what potential benefits do you see?

7. Research indicates that the foremost obstacles to adopting 3D printing are insufficient knowledge or technical expertise (65.4%) and apprehensions regarding part quality and durability (50%).

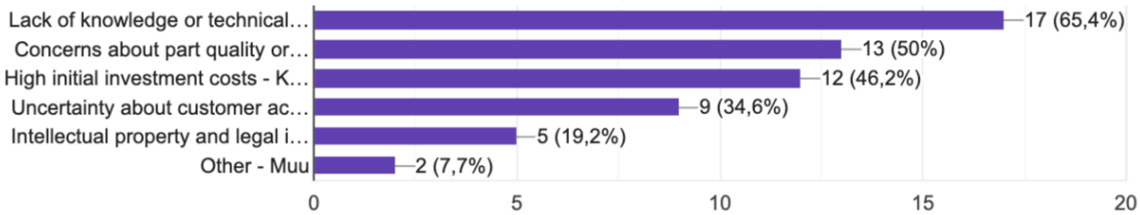


Figure 7.9 Results for question: If you have considered using 3D printing but have not yet implemented it, what are the main barriers or challenges?

8. It has been determined that metals and plastics reign as the top materials for 3D-printed automotive repair parts. Specifically, research indicates that both materials hold a considerable percentage of 71.4%.

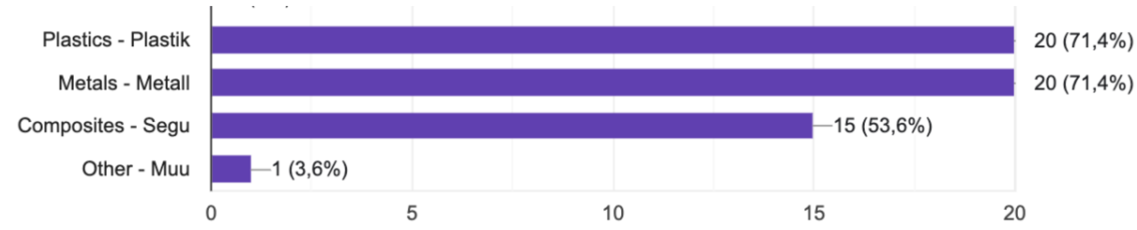


Figure 7.10 Results for question: For 3D-printed automotive repair parts, which material(s) do you think would be most suitable for your needs?

9. The selection process for a reliable 3D printing provider requires weighing several key factors carefully. Data suggests that three critical components command attention: quality and durability of materials rate highest at 92.9%, followed by the cost of parts & services at 82%, with lead time & speed ranking third at an impressive score of approximately 79%.

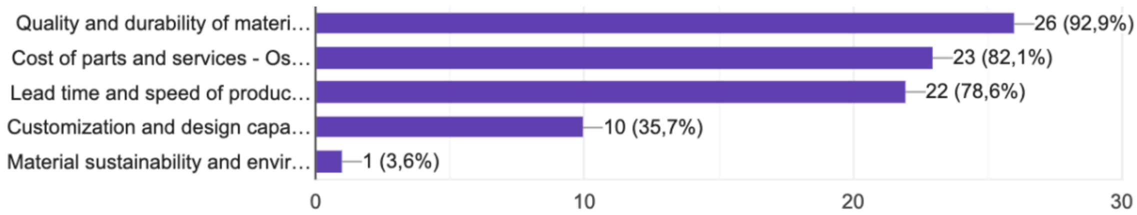


Figure 7.11 Results for question: When considering a 3D printing service for automotive repair parts, what are the most important factors you look for? Please select the 3 most important ones.

10. According to the data, the educational resources that were most favoured for learning how to integrate 3D printing technology were in-person workshops or training sessions at a rate of 71.4%. Additionally, on-site training or support from equipment manufacturers ranked highly, with 78.6% of respondents selecting it as a preferred resource.

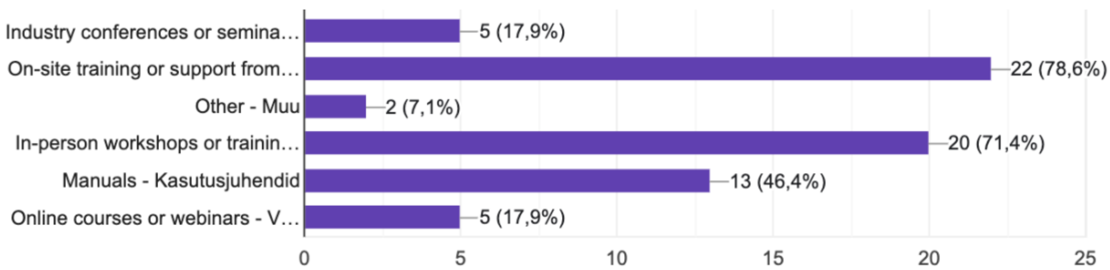


Figure 7.12 Results for question: Regarding integrating 3D printing technology into your repair shop, what kind of training or educational resources would you find most helpful?

In the questionnaire results, sustainability was not a major concern for most respondents. Only 3.6% of the respondents considered material sustainability and environmental impact as an important factor when looking for a 3D printing service for automotive repair parts. In conclusion, the automotive repair industry is open to adopting 3D printing technology, with a particular interest in improving repair capabilities for older or rare vehicles. However, challenges such as a lack of knowledge or technical expertise, concerns about part quality and durability, and high initial investment costs must be addressed. The industry is interested in both metals and plastics for 3D-printed parts and values quality, cost, and lead time. The incorporation of 3D printing in automotive repair could be hastened by availing practical training resources, namely on-site manufacturer support and physical workshops.

SUMMARY

The objective of this master thesis was to explore how achievable it is to integrate 3D printing into automotive manufacturing while considering the potential impact on sustainability. As such, it examined several factors related to 3D printing technology - materials used, types of printers - alongside comparing its advantages to those associated with conventional methods when sourcing car parts.

Adopting new technologies like 3D printing in any new environment like auto-repair comes with challenges and limitations, which must be considered carefully before taking actionary steps towards implementation. Companies must consider factors such as printer build volume limits and accessibility to .STL files, difficulty in sourcing materials and required technical skills.

A practical comparison was conducted on the effectiveness of 3D printing technology versus an older, more conventional option when printing out an oil filter wrench. From the comparison, it was found that a 14-piece set oil filter costs 30 euros and printing one item costs 2,62 euros. This price did not include the cost of a printer, which would also need to be considered when 3D printing is done. During this analysis, the author found that while using 3D-printed parts can be helpful for producing specific replacement auto parts for older or classic cars, any investment must be considered carefully before making decisions that could have financial implications.

After conducting a questionnaire among repair-shop employees offering repair services, it was found that environmental sustainability is not typically a top priority when selecting providers - only 3.6% of respondents noted their preference for eco-friendly options. Based on the survey results, repair shop employees have considered using 3D printing technology (67,9%) but have not done that because they lack the knowledge or technical skills (65,4%). Another important keynote is that car mechanics consider quality and durability the most important factor regarding 3D printed parts (92,9%).

After executing three one-on-one interviews with repair shop owners, it does seem clear that within the context of automotive repairs, there are definite advantages to adopting new technology such as 3D printing – particularly when dealing with more unique or old-dated vehicles requiring particular specifications that are widely unavailable. But as 3D printers are still not being widely used and the investment costs are also high, the

usage of additive manufacturing will be delayed until the time is unknown on all occasions with the interviewees.
A further suggestion by the author includes offering additional car accessories to car owners, such as hangers or phone mounts, to help create awareness of the materials and gain trust towards quality when considering 3D printing.

To make a genuinely positive impact through 3D printing technology in automotive repair practices, sustainability and its awareness must play a central role when moving forward. By prioritising environmentally conscious approaches throughout all stages of production and implementation processes, it will give full advantage of this innovation while minimising carbon footprint.

KOKKUVÕTE

Käesoleva magistritöö eesmärk oli uurida, kuidas on võimalik integreerida 3D-printimine autotööstusesse, arvestades samal ajal võimalikku mõju jätkusuutlikkusele. Töö käigus uuris autor mitmeid 3D-printimise tehnoloogiaga seotud tegureid - kasutatud materjale, printeritüüpe - kõrvuti selle eeliste võrdlemisega tavapäraste meetoditega autoosade hankimisel.

Uute tehnoloogiate, näiteks 3D-printimise kasutuselevõtt igas uues keskkonnas, sh autoremondis, kaasneb väljakutsete ja piirangutega, mida tuleb hoolikalt kaaluda enne meetmete rakendamist. Ettevõtted ja töökojad peavad kaaluma mitmeid tegureid näiteks printerite mahupiirangud, juurdepääs .STL-failidele, materjalide hankimise raskused ja nõutavad tehnilised oskused.

Autor viis läbi praktilise võrdluse 3D-printimise tehnoloogia tõhususe kohta võrreldes vanema, tavalisema variandiga õlifiltri mutrivõtme väljatrükkimisel. Võrdlusest selgus, et 14-osaline õlifilter maksab 30 eurot ja ühe toote trükkimine 2,62 eurot. See hind ei sisaldanud printeri maksumust, mida tuleks samuti arvestada 3D-printimisel. Analüüsi käigus leidis autor, et kuigi 3D-prinditud osade kasutamine võib olla abiks vanemate või klassikaliste autode varuosade tootmisel, tuleb iga investeeringu kasutegur hoolikalt läbi mõelda, enne kui teha lõplikud otsused, mis nõuavad suuri väljaminekuid.

Pärast remonditeenust pakkuvate remonditöökodade töötajate seas küsimustiku läbi viimist selgus, et keskkonnasäästlikkus ei ole teenusepakkujate valimisel tavaliselt esmatähtis - vaid 3,6% vastanutest märkis oma eelistust jätkusuutlikkuse võimalustele. Uuringu tulemuste põhjal on remonditöökodade töötajad küll kaalunud 3D-printimise tehnoloogia kasutamist (67,9%), kuid ei ole seda teinud, kuna neil puuduvad piisavad teadmised või tehnilised oskused (65,4%). Teine oluline tähelepanek on, et automehaanikud peavad 3D-prinditud osade puhul kõige olulisemaks teguriks just kvaliteeti ja vastupidavust (92,9%).

Pärast kolme üks-ühele intervjuud remonditöökodade omanikega selgus, et autoremondi kontekstis on neil olemas kindlad eelised uue tehnoloogia, näiteks 3D-printimise kasutuselevõtuks. Kui tegemist on unikaalsemate või vanade sõidukitega, mis vajavad spetsiifilisi komponente ja need ei ole laialdaselt kättesaadavad kaalutakse kindlasti nende 3D printimist. Kuid kuna sektoris ei kasutata 3D-printereid endiselt laialdaselt ja investeerimiskulud on samuti suured, lükkub intervjueeritavate sõnul nende kasutamine teadmata tulevikku.

Autori täiendav soovitus oleks autoomanikele täiendavate autotarvikute, näiteks riidenagide või telefonikinnituste tootmine, et aidata kaasa erinevate materjalide teadvustamisele ja anda edasi kindlustunnet, mis puudutab printitud osade kvaliteeti.

Selleks, et 3D-printimise tehnoloogia autoremondi töökodades laialdast kasutust leiaks, peab jätkusuutlikkusel ja selle teadvustamisel olema keskne roll. Võttes eesmärgiks keskkonnateadlikke lähenemisviiside populariseerimist kõigis 3D printimist puudutavates tootmis- ja rakendusprotsessi etappides, annab see uuenduslikule varuosade hankimisele kindla eelise, vähendades samal ajal süsinikujalajälge.

REFERENCES

3DDT = Opened 18.05.2023 https://www.3ddt.com.tr/eos-p-770/

3D Natives = *What Are the Most Innovative 3D Printing Applications in the Automotive Sector?* Opened 18.05.2023 https://www.3dnatives.com/en/3d-printing-applications-in-automotive-ranking-081020204/

3D printing = *Software for 3D printing.* Opened 18.05.2023. https://3dprinting.com/software/

Abin, T., Umakanta, M. 2022. *A sustainable circular economic supply chain system with waste minimization using 3D printing and emissions reduction in plastic reforming industry.* Journal of Cleaner Production. Vol 345.

Adobe = *STL files. Adobe.* Opened 18.05.2023. https://www.adobe.com/creativecloud/file-types/image/vector/stl-file.html#stl

All3DP= picture opened 18.05.2023 https://all3dp.com/2/the-smallest-3d-printed-things/

All3DP2 = Snider, J. 2018. *Desktop Metal Studio System: Review the Specs.* Opened 18.05.2023 https://all3dp.com/1/desktop-metal-studio-system-review-3d-printer-specs/

AMFG = *10 Exciting Examples of 3D Printing in the Automotive Industry in 2021.* Opened 18.05.2023 https://amfg.ai/2019/05/28/7-exciting-examples-of-3d-printing-in-the-automotive-industry/

Aniwaa = Opened 18.05.2023 https://www.aniwaa.com/product/3d-printers/desktop-metal-studio-2/

Bineli, A., R., R., Peres, A., P., G., Jardini, A., L., Filho, R., M. 2011. *Direct metal laser sintering (DMLS): technology for design and construction of microreactors*. ABCM.

BPF = *Acrylonitrile Butadiene Styrene (ABS) and Other Specialist Styrenics.* British Plastics Federation. Opened 18.05.2023 https://www.bpf.co.uk/plastipedia/polymers/ABS_and_Other_Specialist_Styrenics.aspx

Carbon = Opened 18.05.2023 https://www.carbon3d.com/products/m2-3d-printer

Chem Spider = picture opened 18.05.2023 http://www.chemspider.com/Chemical-Structure.2015567.html

Chemical Book = picture opened 18.05.2023 https://www.chemicalbook.com/ChemicalProductProperty_EN_CB6189048.htm

CNC Machines = Opened 18.05.2023 https://cncmachines.com/eos-p-770-2017/l/7187

Colbert, F., P., Tony Hsieh, S.-J (Eds.). 2014. *Thermosense: Thermal Infrared Applications XXXVI.*

Custompart = *Fused Deposition Modeling (FDM).* Opened 19.05.2023 https://www.custompartnet.com/wu/fused-deposition-modeling

Dinwiddie, R., B., Kunc, V., Lindal, J., M., Post, B., Smith, R., J., Love, L., Duty, C., E. 2014. *Infrared imaging of the polymer 3D-printing process.*

Dipak, M., H., Trupti, S., G. 2022. *Additive manufacturing (3D printing): Recent progress on advancement of materials and challenges*. Materialstoday: Proceedings. Vol 58.

eBay = picture opened 18.05.2023 https://www.ebay.ca/itm/114945591842?hash=item1ac34a8a22:g:0osAAOSw6BphHzWT

Faludi, J., Hu, Z., Alrashed S., Braunholz, C., Kaul, S., Kassaye, L. 2015. *Does material choice drive sustainability of 3D printing?* Int J Mech Mechatron Eng, 9.

Formadditive = *HP Multi Jet Fusion 5200 3D Printer.* Opened 18.05.2023 https://www.formadditive.com/EN/urun/14/hp-multi-jet-fusion-5200-3d-printer

Gebler, M., Uiterkamp, A., Visser, C. 2014. *A global sustainability perspective on 3D printing technologies Energy Policy.*

Guiness Wold Records = *Largest Solid 3D printed object.* Opened 18.05.2023 https://www.guinnessworldrecords.com/world-records/432579-largest-solid-3d-printed-object

Hossam, K., Soham, W., Changxue, X., Fakrul, A. 2019. *Digital light processing (DLP) 3D-printing technology and photoreactive polymers in fabrication of modified-release tablets.* European Journal of Pharmaceutical Sciences. Vol 135.

Hu, L., Jiang, G. 2017. *3D printing techniques in environmental science and engineering will bring new innovation.* Environ Sci Technol, 51.

Bajaj, P., Roopanwal, A.K., 1997. *Thermal stabilization of acrylic precursors for the production of carbon fibers: an overview.* J. Macromol. Sci. C Polym. Rev. 37 (1).

Interesting Engineering = *These 3D Printed Cars Start at Just $10,000.* Opened 18.05.2023 https://interestingengineering.com/transportation/these-3d-printed-cars-start-at-just-10000

Jinghua, X., Kang, W., Hongsheng, S., Mingyu, G., Shuyou, Z., Jianrong, T. 2019. *Energy efficiency optimization for ecological 3D printing based on adaptive multi-layer customization.* Journal of Cleaner Production. Vol 245.

Manufactur = *How Stereolithography or SLA 3D Printing Works?* Opened 18.05.2023 https://manufactur3dmag.com/stereolithography-sla-3d-printing-works/

Manufactur2 = *How Selective Laser Sintering Works? (2023).* Opened 18.05.2023 https://manufactur3dmag.com/how-selective-laser-sintering-works/

Markforged = *How 3D Printing Drives Change in the Automotive Industry.* Opened 18.05.2023 https://markforged.com/resources/blog/how-3d-printing-drives-change-in-the-automotive-industry

MasterGraphics = *How much does the HP 3D printer cost?* Opened 18.05.2023 https://blog.mastergraphics.com/expert_advice/how-much-does-the-hp-3d-printer-cost

Moldavska, A., Welo, T. 2017. *The concept of sustainable manufacturing and its definitions: A content-analysis based literature review.* Journal of Cleaner Production. Vol 166.

Ngo, T., D., Kahani, A., Imbalzano, G., Nguyen, K., T., Q., Hui, D. 2018. Additive manufacturing (3D printing): a review of materials, methods, applications and challenges Compos Part B Eng.

P., Alexandrea. 2022. *The Complete Guide to Selective Laser Sintering (SLS) in 3D Printing.* 3Dnatives. Opened 18.05.2023 https://www.3dnatives.com/en/selective-laser-sintering100420174/#!

Parker, G. 2023. *The Five Most Expensive 3D Printers.* Money Inc. Opened 18.05.2023 https://moneyinc.com/the-five-most-expensive-3d-printers-on-the-market-today/

Peugeot Lifestyle = picture opened 18.05.2023 https://boutique.peugeot.com/glasses-holder-3d-accessory-peugeot.html

PolySpectra = *Can Plastics Really Replace Metal? A 3D Printing Materials Comparison. 2021.* Opened 18.05.2023 https://polyspectra.com/blog/3d-metal-materials-comparison/

Reyes, J. 2022. *What is Sustainable Manufacturing?* SafetyCulture. Opened 18.05.2023 https://safetyculture.com/topics/sustainable-manufacturing/

ResearchGate = picture opened 18.05.2023 https://www.researchgate.net/figure/Chemical-structure-of-poly-lactic-acid-PLA_fig2_352498878

Savini, A., Savini, G., G. 2015. *A short history of 3D printing, a technological revolution just started.* ICOHTEC/IEEE International History of High-technologies and their Socio-cultural Contexts Conference (HISTELCON).

SCMP = Ren, D. *Can you 3D-print a car? This company will mass print cars by 2019 for US$10,000 each.* Opened 18.05.2023 https://www.scmp.com/business/companies/article/2137737/worlds-first-mass-produced-3d-printed-electric-car-be-sold-china

Sculpteo = *The History of 3D Printing: 3D Printing Technologies from the 80s to Today*. Opened 18.05.2023 https://www.sculpteo.com/en/3d-learning-hub/basics-of-3d-printing/the-history-of-3d-printing/

Sculpteo2 = *Units and Size: Understand your 3D Printing Dimensions.* Opened 18.05.2023 https://www.sculpteo.com/en/3d-learning-hub/design-guidelines/3d-printing-dimensions/

Slaper, T., F., Hall, T., J. 2011. *The Triple Bottom Line: What Is It and How Does It Work?* IBR Indiana Business Review.

SmarTech Analysis = *Additive Manufacturing Opportunities In Automotive*. Opened 18.05.2023. https://www.smartechanalysis.com/reports/automotive-additive-manufacturing/

Stellantis = *New technology: 3D printing in the new peugeot 308.* Opened 18.05.2023 https://www.media.stellantis.com/em-en/peugeot/press/new-technology-3d-printing-in-the-new-peugeot-308?adobe_mc_ref=

STL = *STL Fileformat.* Opened 18.05.2023. https://docs.fileformat.com/cad/stl/

StrataSys = Opened 18.05.2023 https://www.stratasys.com/en/3d-printers/printer-catalog/fdm-printers/fortus-450mc/

TCT Magazine = Davies, S. *Carbon and Ford showcase selection of 3D printed end-use automotive applications.* Opened 18.05.2023 https://www.tctmagazine.com/additive-manufacturing-3d-printing-news/carbon-ford-showcase-3d-printed-automotive-applications/

The Verge = *Ford makes it easier to 3D-print your own accessories for the Maverick*. Opened 18.05.2023 https://www.theverge.com/2022/2/16/22936380/ford-maverick-cupholders-3d-print-accessories-cad-fits

Thingiverse = picture opened 18.05.2023 https://www.thingiverse.com/thing:215703

Thingiverse2 = picture opened 18.05.2023 https://www.thingiverse.com/thing:5121962

TreatStock = *About Fortus 450mc.* Opened 18.05.2023 https://www.treatstock.co.uk/machines/item/139-fortus-450mc

Truer = *Electron Beam Melting (EBM) technology introduction.* Opened 19.05.2023 https://am-material.com/ebm-technology/?fbclid=IwAR1kWg0tn_ovrcXMCBs7FpMz-c-9lrjMNFoTFrq5ieg49cF0FWqS1FLM_Yg

Velenturf, A., P., M., Purnell, P. 2021. *Principles for a sustainable circular economy.* Sustainable Production and Consumption. Vol 27.

Wong, D. 2019. *Physicist 3D-prints a Lamborghini Aventador in his own garage.* Which Car?.