Feasibility assessment of manufacturer-controlled spare parts manufacturing using AM technology

A case-study in vacuum cleaners

Borja de la Cruz González

MSc. Integrated Product Design

Faculty of Industrial Design Engineering

TU Delft

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MSc. Graduation Thesis

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Borja de la Cruz González

MSc. Integrated Product Design

Faculty of Industrial Desing Engineering

Delft University of Technology

Chair

Dr.Ruud Balkenende

Department of Sustainable Design Engineering

Mentor

Dr.ir.Bas Flipsen

Department of Sustainable Design Engineering

Company Mentors

Jeroen de Graaf

Group Leader UX Research at Versuni

Esra Kiygin

Sustainability Officer FloorCare at Versuni

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Executive summary

One layer at a time

This graduation project delves into the use of Additive Manufacturing (AM) to produce spare parts through a case study of vacuum cleaners. Waste from Electrical and Electronic Equipment (WEEE), including products like vacuum cleaners, challenges the European Union's (EU) sustainability goals. In 2020 alone, the EU collected an estimated 12.4 million tonnes, representing 10.5 kilograms per person. To address this issue, the "Right to Repair" was adopted. This initiative aims to promote repair as a strategy to slow down WEEE by mandating companies offer to 10 years of post-warranty spare parts availability and 15 days of lead time. This mandate challenges companies' responsiveness due to the extended period of support and limited lead time. Am provides an opportunity to fulfil these requirements while also offering additional benefits such as the digitalisation of the supply chain and reducing the environmental impact of the company's operations.

The main research goal of the project is the development of a framework for evaluating the suitability of components within a product to be AM printed as spare parts. The framework is established through a literature review across three primary research areas: Priority components (identifying key components for repair activities), Printability (assessing component suitability for AM printing) and Spare Part Suitability (evaluating components' suitability for supply chain considerations). The proposed framework, encompassing three primary steps, narrows down the components from a complex product to focus on those that present greater AM eligibility. This, in turn, guides the company's effort in designing, testing and making these eligible parts commercially available.

Step 1. Cut -off criterion: Aims exclude components defined as not suitable for AM printing, such as standardized elements and electronics.

Step 2. Eligibility Evaluation: Assess components eligibility for AM spare parts printing within the research areas.

Step 3. Component Selection: A top-down approach is employed. It begins with the selection of repair priority components, from his group those deemed AM printable are identified, and finally, components aligned with supply chain suitability are selected.

Takeaways from the conducted research also involve the insights gathered from the conducted framework validation, which involved two Philips vacuum cleaners and the use of Selective Laser Sintering (SLS) for the printing of spare parts. Lastly, this thesis establishes a foundation for the exploration of AM potential in the realm of spare parts manufacturing and future product design.

Glossary

AM=Additive Manufacturing

IM= Injection Moulding

SLS= Selective Laser Sintering

CAD= Computer Aided Design

Contents

Part 1.

Project introduction

1. Introduction

This chapter provides an overview of the factors that motivated the exploration of using AM for spare parts manufacturing. Introduces the defined project challenge and scope, followed by the research method implemented to achieve the defined goals and research scope.

1.1. Context & background

This thesis project is conducted in collaboration with Versuni to investigate the viability of Additive Manufacturing (AM) in the production of spare parts for their product range. Versuni specializes in domestic appliances such as vacuum cleaners, coffee machines or air purifiers. Despite the pivotal role of domestic appliances in the current modern lifestyle, electrical and electronic waste generated (WEEE) pose a challenge for the European Union's (EU) sustainability goals (Eurparl, 2023). WEEE waste has been growing at a rate of 3-5% per year (Karl et al., 2021). In 2020, the EU collected an estimated 10.5 kilograms of WEEE per inhabitant (Eurparl, 2023; Eurostat, 2023; Directorate-General for Environment, 2022).

Repair as a sustainable strategy

In response to the sustainability challenges and recognizing the potential of repair for product life extension and waste reduction (Bocken et al., 2016), the European Commission (EC) introduced the “Right to Repair” initiative in 2022 as part of the EU Circular Economy Strategy. Users are central to the repair strategy, playing a crucial role in product usage and repair activities (Terzioğlu, 2020). However, barriers such as product complexity, limited technical knowledge, high repair cost and scarcity of spare parts key for product functionality hinder users’ willingness to engage in repair activities (De Fazio et al., 2021; Jaeger-Erben et al., 2021). Additionally, companies often limit access to spare parts, repair tools and guides (Terzioğlu, 2020).

Therefore, the initiative mandates companies to ensure spare parts availability for up to 10 years post-warranty with a maximum lead time of 15 days for component delivery to end-users, as a measure to promote repairability (IP/23/1794, 2023).

Supply chain challenges

Facing the imperative of extending spare parts support with the established lead time limit presents a substantial challenge to the agility and adaptability of supply chains. This challenge surges from the obligation to both stock and produce spare parts for older, current, and future products as well as the logistics management (Knofius, 2016; van Oudheusden, 2023; ECC-NET, 2023).

Figure 1: Current picture of WEEE waste in the EU (source: Eurostat, 2023, Photo by Inès Magoum)

Window of opportunity for Additive Manufacturing

AM enables on-demand, localized production, and the establishment of a digitalized spare parts inventory, resulting in reduced lead times, simplified supply chain operations, and environmental sustainability by minimizing transportation and storage emissions (Sasson & Johnson, 2016; Campbell et al., 2011). Moreover, its ability for complex geometries and small batch production can lead to cost savings for end-users, particularly for older products for which the spare parts support is discontinued (AMFG, 2021).

However, the technology also presents several limitations, including slower production speed, hampering its application in high-demand scenarios, limited material range and lower reliability and quality of production compared to traditional manufacturing processes (Khajavi et al., 2014; Berman, 2012; Eckhoff, 2020). These implications can influence the opportunities that AM offers for spare parts manufacturing under supply chain conditions.

Prior research

Among the initiatives exploring the use of AM, the SHAREPAIR project aims to mitigate consumer product waste (WEEE) by enhancing citizen repair initiatives using digital tools such as AM printing (TU Delft). Within this context, TU Delft developed 3DP4R Guide (Bolaños et al., 2022), which offers a framework for AM printed spare parts with a focus on self-repair and DIY (Do it yourself) initiatives. The guide encompasses four primary phases: Analysis, Redesign, Manufacture, and Test, offering a comprehensive process to produce AM-printed replacement parts.

The focus on self-repair operations using Fuse Deposition Modelling (FDM) technology highlights a knowledge gap regarding its application, particularly in how it affects Original Equipment Manufacturers (OEMs) and the exploration of alternative AM technologies.

1.2. Problem definition, scope and research questions

Lack of understanding of AM potential

Despite the advantages of AM, companies like Versuni have not yet widely adopted the technology. This reluctance originated from the need to determine which components within their products are feasible for spare parts printing to conduct a revision of their new spare parts support strategy. Additionally, the number of available technologies and each one's specific characteristics presents a challenge when deciding how components should be manufactured and if AM can provide the required components' performance.

Previous work research gap

Contrary to previously conducted research from TU Delft (3DP4R Guide; Buijserd, 2022; Bolaños et al., 2022), mostly focused on self-repair activities. This research explores the company perspective, and thus, additional factors such as supply chain challenges need to be considered (Chaudhuri, 2019; Rao, 2022; Svensson et al., 2017)

Repair as core strategy

As part of identifying components within a product suitable for AM, there is an opportunity to introduce another key player in the core objective, repair priority. This prioritization approach serves as a pivotal criterion in the decision-making processes of companies, guiding their selection of components to concentrate on for AM-based interventions.

Project delimitations

1. Being that the research project is focused on spare parts, these can be categorized into two main groups: internal use and after-sales (Storhagen, 2011). The first group supports the company's own equipment (e.g., machinery for prototyping), while after-sales are directed for customers. This thesis emphasizes after-sales spare parts given their significance in consumer repair activities.
2. The conducted research focuses on vacuum cleaners proposed by the company SpeedPro and SpeedPro Max (se Section Part 3).
3. Research focuses on polymer-based AM technologies, providing further insights into polymer printing and performance compared to Injected Moulded components (the primary manufacturing process of the proposed product for the project).

Research questions

The conducted project context research and discussion with Versuni and TU Delft, the following research questions are defined:

MRQ: How can components eligibility be assessed?

RQ.1 Which AM technology is best suited for spare parts manufacturing?

RQ.2 What criteria can be used to evaluate components eligibility?

RQ.3 Which components from the product present to be eligible?

RQ.4 How does SLS printed components compare to the original ones?

RQ.5 Is the proposed framework effective?

RQ.6 Which design guidelines can guide designers for current and future products for AM spare parts?

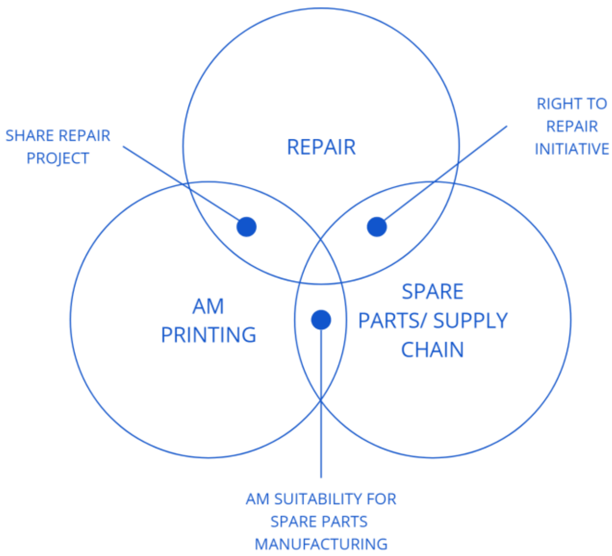


Figure 2: Overview of identified areas of research.

1.3. Project approach & method

The structure of the project is divided into 5 parts (Figure 3), each part aims to answer one of the identified research questions:

1. Research on AM technology to determine the most suitable approach for spare parts production (Part 2): To address RQ 1, the literature review is conducted to compare polymer-based AM technologies with the conventional IM process. The chosen technology will subsequently help define the proposed framework and the practical study.

2. Identifying eligibility criteria for component evaluation (Part 2): Regarding RQ.2, literature research is conducted to acquire insight into criteria that can determine the eligibility of components within the scope of the project: printability of components, their value for repair activities and suitability for spare parts. The criteria identified will serve as the foundation of the eligibility framework.

3. Develop the eligibility framework for assessing component suitability for AM spare parts (Part 2): Answering RQ.3, the gathered insights in AM technology, identified criteria and literature review will serve to formulate the proposed eligibility framework. The primary objective is to define the eligibility of components for companies to formulate the best strategy.

4. Apply and test of the eligibility framework on the company's designated vacuum cleaners (Part 3 & 4): The framework is implemented in a practical study to address R.Q 4, 5, and 6 by studying two company-proposed products.

5. Evaluate the proposed framework and engage in iterative refinement (Part 5): Insights gathered from the conducted practical study is used as a reference to evaluate the proposed framework and propose additional consideration and functionalities.

6. Establish design guidelines for AM spare parts (Part 5): Answering RQ.7, the conducted print and test of components can provide insight into considerations designers might need to consider when designing AM for current and future products.

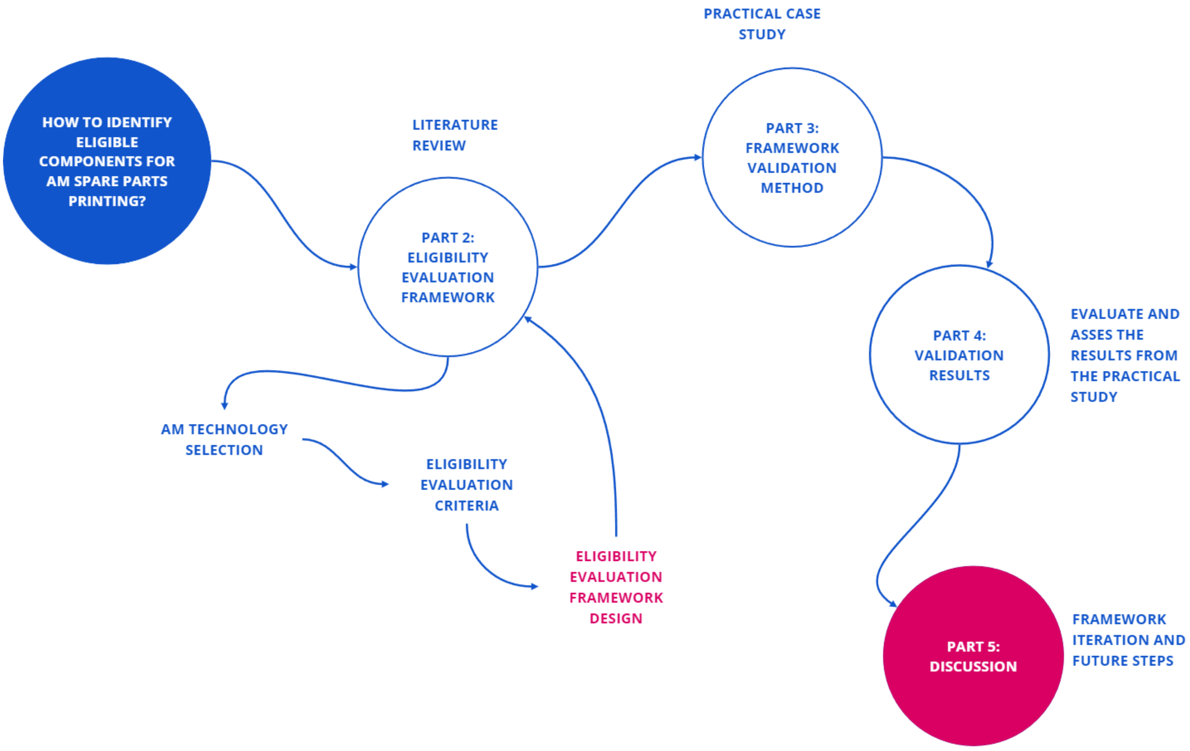


Figure 3: Overview of project approach

Part 2. Literature research

Defining the Framework

Introduction to Part 2

This section of the research aims to define the proposed eligibility evaluation framework to identify suitable components with products for AM spare parts. To achieve this, the research is structured into three main chapters.

The initial chapter aims to identify the most suitable AM technology for spare parts production, compared to the original traditional manufacturing process. Moreover, specific technology-related considerations are considered in forming the upcoming eligibility framework.

The second chapter presents the results from the conducted literature review regarding criteria for the eligibility of components for spare parts. From the project scope, three primary areas are defined: priority for repair, printability, and spare parts suitability.

The third and last chapter presents the development of the eligibility evaluation framework, based on the insights gathered from the previous two chapters. The framework is designed to identify which components within an assembly present more suitability to be AM printed as spare parts to be prioritized in manufacturing and digitalization.

1. AM technology selection

1.1. Introduction

The goal of the section is to identify the technology that best suits the original manufacturing process specifications and the technology used for the practical study. The scope of the research is on polymer-based technologies as discussed in the project introduction. Therefore, this section will not present additional research on alternative material processes.

R.Q.1 Which AM technology is best suited for spare parts manufacturing?

1.2. Method

1.2.1. Polymer based technologies.

The first screening of AM technologies is conducted by selecting polymer-based processes as defined in the scope of the project. To select the technology, only polymer printing is considered, for which a 3D HUBS (2017) guide is followed (see Figure 4). FDM, SLS, MJF and SLS are selected for further exploration.

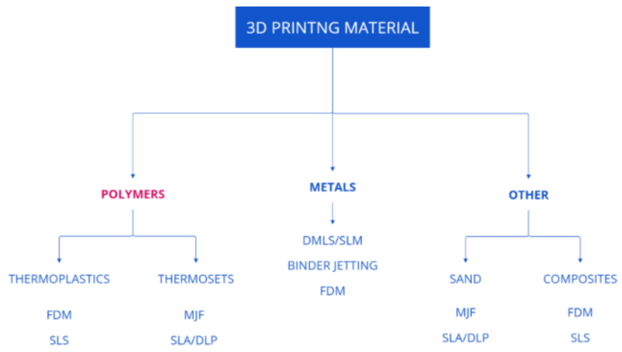


Figure 4: Overview of available AM technology categories and each technology within (credit 3D Hubs, What is 3D printing?)

1.2.2. Technology comparison table

A side-by-side comparison is conducted (see Table 1) where polymer-based technologies are compared to Injection Moulding (IM), the primary manufacturing process for vacuum cleaner polymer components (EAKVAC, Vacuum Cleaner Manufacturing process).

Data is collected from AM and IM suppliers (3D Hubs, Formlabs and Xometry). AM part cost is determined through a quotation from 3D HUBS using a publicly available SpeedPro Max Vortex CAD file, where one part is requested (Appendix A). IM cost is based on Formlabs' estimations for mid-volume production (Formlabs, How to Estimate Injection Moulding Cost?) Regarding IM specifications, some of the criteria do not apply due to AM-specific characteristics, an X will be used in these scenarios. In cases lacking quantitative values, qualitative values from the mentioned sources are utilized.

The criteria for the comparison are based on those outlined by Algunaid & Liu (2022). Material-specific criteria (e.g., elongation at break, chemical and water resistance, cost, impact resistance etc) are omitted due to their dependence on material type, supplier, AM technology and printer model (entry level vs high-end). Appendix B presents a material overview for personal reference. Criteria in the comparison are narrowed down to transparency and flexible attributes, which are more technology dependent.

1.2.3. Further understanding on selected technology

Lastly, an overview of the selected AM technology is conducted to gain a more comprehensive understanding of its characteristics and potential implications in the forthcoming definition of eligible criteria and practical case study. For that, the previously mentioned sources used for the comparison table are referenced.

1.3. AM technology selection

Table 1 presents the conducted technology comparison table. The result presents SLS as the preferred technology for AM spare parts printing due to precise tolerances, building volume and cost. This conclusion Is shared by Rao (2021), who identified companies' preference for SLS for its capacity for complex geometry printing, high accuracy, and support-free printing, which optimizes material use and minimizes post-processing.

FDM presents poor tolerances, surface finish and lower printing speed. SLA excels in precision and transparent material printing quality (Formlabs, n.d.). However, exhibits limitations in terms of speed, build capacity and cost-effectiveness compared to SLS and MJF, critical for larger batch manufacturing scenarios (Plunkett, n.d.).

Finally, between MJF and SLS, the latter is selected due to its availability from company's direct prototyping supplier, workshop accessibility and expertise.

Table 1: Overview of AM polymer-based processes and Injection moulding processes.

	IM	FDM	SLS	SLA	MJF
DESCRIPTION	The molten polymer is injected into a mould under pressure, offering cost-effective production, design versatility, and reproducibility.	A process where melted filaments are extruded from a nozzle onto a building platform, layer by layer.	SLS printer uses a CO2 laser to sinter deposited powder layer by layer.	UV light is used to selectively cure and solidify photopolymer resin.	The process spreads a layer of powder, deposits fusing agents and an IR energy source sinters agent exposed areas forming the geometry.
QUALITY CRITERIA (MM)					
TOLERANCE	0.12	0.5	0.3	0.3	0.3
SURFACE FINIS H	HIGH	LOW	MED	HIGH	MED
BUILDING VOLUME	X	200 x 200 x 200	300 x 300 x 300	145 × 145 × 175	380 × 284 × 380
LAYER THICKNESS	X	0.3	0,1	0,05	0,08
WALL THICKNESS	0.4	0.8	0.6	0.25	1
HOLE SIZE	X	2	1.5	0.5	1.0
MINI FEATURE SIZE	0.2	2	0.5	0.2	0.5
SUPPORT	X	Yes	No	Yes	No
MATERIALS	thermoplastic material.	Polymers	Ceramic, metal, and polymers.	Plastics and Polymers.	Polymers.
1.FLEXIBLE MATERIAL	YES	YES	YES	YES	YES
2.TRANSPARENT MATERIAL	YES	YES	NO	YES	NO
ECONOMICAL CRITERIA					
COST OF MANUFACTURING (1)	2.41	15.52	28.19	46.21	25.94
PRODUCTION SPEED	VERY HIGH	LOW	MED	MED	HIGH
LEAD TIME (DAYS)	3-5	3	3	3	3
TECHNOLOGY STRENGHTS					
	Great surface finishes with the need for little to no extra post-processing for finishes. The moulding cycle lasts 15 to 60 seconds and multiple	Most cost-efficient technology to manufacture end -ser parts.	Well suited for functional snap-fits and end-user parts. The technology's lack of support makes it ideal for complex geometries. Its ample	High resolution and accuracy, fine details and smooth surface finishes. Wide range of materials offering rigid,	Like SLS, it is optimal for Snap-fit manufacturing and robust parts.

	parts are manufactured at the same time.		building volume and speed makes it effective for small and medium batch printing.	flexible, and mechanical.	
TECHNOLOGY DRAWBACKS					
	Lead Times 3-5 days. High cost for small batch production. Costly design changes due to the need for updated mould design.	Low Accuracy, Poor surface Finish, low speed.	Post-processing is required to clean component surfaces. High overall costs	Small build chambers, low material compatibility and high material cost. Resin curing post process required.	Poor mechanical properties.

[1]Single part manufacturers are not viable for IM processes, therefor the cost is obtained from an estimation conducted by Formlabs (n.d.) on a mid-volume production.

1.4. Overview of SLS process

The conducted technology selection concluded with SLS being the preferred technology for AM spare parts manufacturing. Therefore, this section aims to provide a further understanding of technological capabilities and considerations. These will support the upcoming practical study by offering an overview of available materials, post-processes, and technology printing characteristics. Focusing on the available SLS printer at the company (Fuse 1+ 30 W by Formlabs)

1.4.1. SLS materials

SLS material availability, not only limited by the process compared to other technologies, is also dependent on the specific printer in use. In the case of the company, the Formlabs Fuse 1+ 30W model is used. Currently, 4 rigid polymers and one flexible material are available. Table 2 presents an overview of the material.

1.4.2. SLS post-processes

SLS offers a variety of post- to improve components performance depending on their requirements. Due to the porous and rough surface of printed parts, some components, especially moving assemblies might require post-processes to enhance components responsiveness (Formlabs, Guide to SLS Post-Processing Techniques).

Figure 5 illustrates two options: Vapour smoothing, which delivers an IM-like finish and reduces moisture absorption and ceramic coating, enhancing high-performance parts by improving chemical resistance, mechanical strength and reduced corrosion and friction (Xometry, n.d.; Formlabs, n.d.)

After parts are printed, these need to be sandblasted to remove the Surface Armour, a term used for semi-sintered material adhered to the component's surface and cavities (see Figure 6)

Figure 5: (Left) Vapour smoothed component presenting an IM-like surface finish. (Right) Ceramic coating which enhances part abrasion resistance as well as providing smooth surface (Xometry, n.d.; Formlabs, n.d.) (Image credit: Formlabs)

Figure 6: Sand blasted (Left) compared to a component extracted directly from the build chamber, where the Surface Armour can be seen in the cavities (Right). (Image credit: Formlabs)

Table 2: Overview of Formlabs available materials (credit Formlabs, n.d.)

NYLON 12	NYLON 11	NYLON 12 GLASS FILLED
		
• High-performance prototyping • Small batch manufacturing • Permanent jigs, fixtures, and tooling • General SLS parts	• Impact-resistant prototypes, jigs, and fixtures • Thin-walled ducts and enclosures • Snaps, clips, and hinges • Orthotics and prosthetics.	• Robust jigs and fixtures and replacement parts • Parts undergoing sustained loading. • Threads and sockets • Parts subjected to high temperature.
Nylon 11 Carbon Filled	TPU 90A	
		
• Replacement and spare alternatives to metal parts. • Tooling, jigs, fixtures • High-impact equipment • Functional composite prototypes	• Padding, dampers, cushions, and grippers • Gaskets, seals, masks, belts, plugs, and tubes • Soles, splints, orthotics, and prosthetics	

1.4.3. SLS benefits

No support required

SLS distinguishes itself from other AM processes by the lack of support requirement, as unfused powder surrounding the building part acts as a natural support structure. This characteristic enables the optimization of the available build volume for batch manufacturing, reduces pros-process time and enables enhanced design freedom (see Figure 7).

Manufacturing volume and waste

The lack of support frees space in the building chamber that otherwise would be required for a support structure. This characteristic minimizes waste since excess SLS material is reusable for other prints. Conversely, FDM and SLA require careful model orientation in the print volume, which reduces the number of parts that can be printed at the same time (Formlabs, n.d.; 3D Hubs, n.d.).

Refresh rate

SLS technology allows for the adjustment of the refresh rate, determining the proportion of newer material that is mixed with the reused one for each new print. This feature offers cost reduction and a more sustainable process by recycling excess material from previous prints. Typically, a 30% refresh rate is advised for general use scenarios, as a lower refresh rate (less new material therefore lower cost) may elevate the risk of surface finish defect (Formlabs, Understanding Refresh Rate).

1.4.4. SLS limitations

Shrinkage and warping

AM processes, including SLS, experience some shrinkage and warping when the cooling of the part is fast and irregular, due to a high difference between environment and print temperature, leading to a deformation of the geometry (Formlabs,2020). To address this in SLS it is recommended to increase design dimensions by 3-3.5% during pre-print analysis for shrinkage or adding ribs and support to flat surfaces (see **Error! Reference source not found.**).

Surface finish

As mentioned beforehand, SLS produces rough surfaces, which in specific cases where smooth surfaces are required for product functionality parts are required to undergo post-processing (3D Hubs, n.d.).

Figure 7: Example of support needed for print in SLA (Left), compared to the building volume and freedom of SLS (Middle). (Right) Example of a FDM failed print due to an unsupported overhanging feature. (Image credit: Left and Middle: Formlabs. Right: 3D Hubs)

Figure 8: Printed component presenting a deviation from intended dimensions due to warping (Formlabs, n.d.)

1.5. Conclusion

The technology selected for this research is SLS owing to its high accuracy, large print volume and market preference by numerous companies and OEMs (Rao, 2021; Vafadar *et al.,* 2021). However, it also presents some disadvantages when compared directly to IM and alternative AM processes.

In total, seven different AM categories are available for manufacturers to produce spare parts. Nevertheless, currently, only four of these technologies are suitable for polymer manufacturing, these being FDM, MJF and SLS. Each technology presents clear advantages and disadvantages, making them best suited for specific scenarios. FDM is best suited for self-repair scenarios and the production of cost-effective parts. SLA offers a clear advantage in print resolution and tolerances, being the best option for detailed and high tolerance requirements components.

Additionally, SLA offers the best print quality for transparent material. In this regard SLS and MJF, do not currently offer such alternatives, nonetheless, these technologies surpass SLA in print volume, speed, and cost-effectiveness, which are more suitable for spare parts production.

SLS is finally selected over MJF due to its availability at company workshop and direct suppliers, which facilitates the production and iteration for the upcoming practical study.

2. Eligibility criteria for AM spare parts

2.1. Introduction

This chapter outlines the results from the literature review to identify criteria to determine components suitability for AM spare parts. In line with the defined project scope, three main areas of research are defined: components repair priority, printability, and spare parts suitability. These criteria will be implemented in the proposed framework. Therefore, the main research questions are:

RQ.2 What criteria can be used to evaluate components eligibility?

2.2. Method

To identify the supporting criteria to evaluate components eligibility for AM spare parts, literature research is conducted in the identified three research areas:

1. Printability: TU Delft 3DP4R Guide and existing literature on spare parts printing is reviewed to identify means of printability evaluation (Bolaños et al.,2022; Buijserd, 2022).

2. AM for Spare Parts: Literature referring to spare parts suitability for AM is conducted to identify AM constraints and opportunities for the supply chain. Research papers referring to classification criteria for AM spare parts are obtained for TU Delft repositories in existing work (Rao, 2021) and available research papers at ScienceDirect and ResearchGate (Tunborg, 2017; Cardeal et al., 2020; Chaudhuri et al., 2019; Svensson et al., 2017, among others)

3. Priority for repair: Existing literature referring to repairability of vacuum cleaners (Fonteijne, 2021; De Fazio, 2019; Rames et al., 2018) and priority components identification and assessment (Flipse, 2020; Cordella et al., 2019; EU standard EN 45554) is used to identify the criteria.

2.3. Determining the printability of components

The 3DP4R Guide defines several factors that can influence the effective printing of components. Although focused primarily on FDM, it offers the basis for evaluating the complexity of a component to be printed and the possible need for a redesign. Additionally, the guide presents clear examples and illustrations on how to evaluate cases such as component complexity, fit requirements, and geometry class. Figure 9 illustrates an example of 3DP4R Guide components printing considerations.

Part geometry criteria

This first group conducts a thorough understanding of the part geometry to understand the complexity and implications when conducting the printing operation and upcoming performance requirement (see Table 3).

Performance requirements

Table 4 presents the requirements components can present due to their functionality or expected performance.

2.3.1. Additional criteria discussion

The 3DP4R process includes additional criteria to evaluate part requirements and challenging scenarios. However, some of them are not considered while others are established as a minimum requirement for the product category (Cleaning appliance).

Food safe: This is not considered as the product category does not require such a characteristic.

Watertight: The product is intended for use in cleaning activities, where water or humidity may be present. Therefore, this will already be considered for design recommendations.

High temperature: SLS nylon materials already offer a level of heat resistance, however, in the case scenario (selected vacuum cleaners) no specific heat exposure is defined. Therefore, the criteria will not be considered in this scenario.

Chemical resistance: The product's cleaning application already requires a certain level of chemical resistance, as detergents or bleaches may be involved. While not all SLS material is inherently chemical resistant (GF 12), post-processes such as ceramic coating can enhance part tolerance (3D Hubs, n.d.)

UV exposure: The product category is expected to be used in different environments, where UV lighting may be a factor. Some technologies like SLA and DLP and materials such as PLA are affected by UV, as the exposure can cause defects in the material properties and degrade its integrity. To the contrary, SLS material (Nylon powder) is UV-resistant. However, added post-processes like painting can still be affected, hence, it must still be considered to some degree (3D Hubs, n.d.).

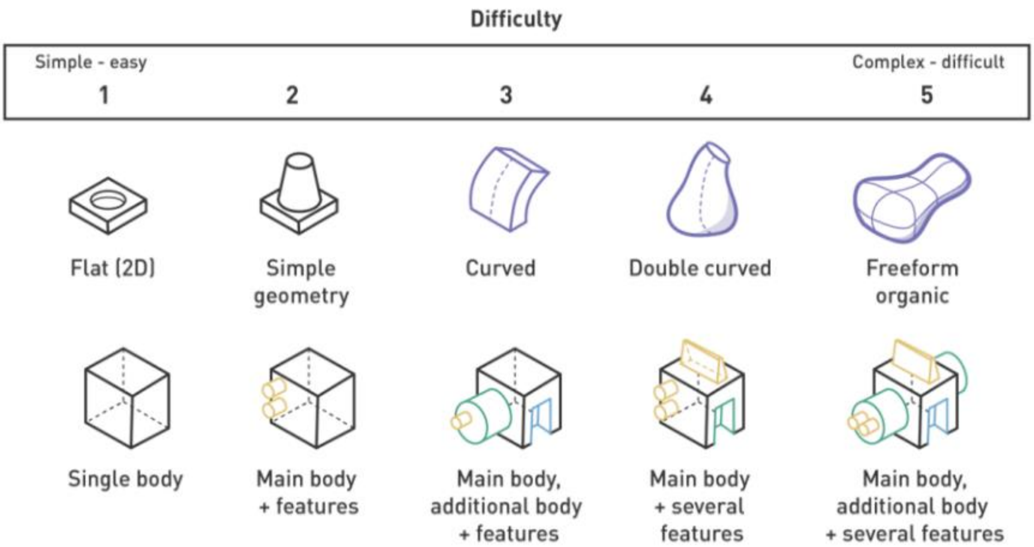


Figure 9: Example of the illustrated examples to determine component complexities and their range from simpler to more complex (credit: 3DP4R, Bolaños et al., 2022)

Table 3: Overview of geometry evaluation criteria and its implication on part printability (credit Bolaños et al., 2022)

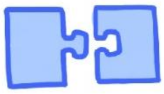
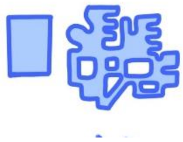
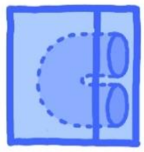
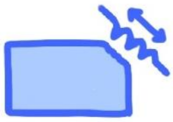
PART GEOMETRY CRITERIA				
IDENTIFY FIT REQUIREMENT	NUMBER OF FEATURES	SHAPE COMPLEXITY	CAVITIES	FINE DETAILS
				
Categorized into moving parts, normal fit, press fit, and interference fit. The higher the fit requirement, the greater the printing challenges due to AM dimensional variations, shrinkage, warping, and tolerance limitations.	A greater number of features can lead to printing complexity, necessitating higher precision, extended pitting time, material consumption and advanced post-processing due to intricate details.	Although AM can create complex shapes, like the number of features, the shape complexity can enhance the printing challenge due to the required precision, possible excess material in cavities and post-process requirements.	In 3DP4R refers to the difficulty of measuring inner cavities for replacement parts design. However, unsupported cavities can present challenges in AM due to potential issues like excess-material accumulation, insufficient support, or post-processing difficulties (Xometry, 2022)	Fine details can be problematic for AM when they are subjected to printing tolerances and minimum feature dimensions. Post-processing techniques, like sanding or painting, can potentially damage these fine details or affect their resolution (Xometry, 2022)

Table 4: Overview of criteria to identify part requirements and implication on AM printability (Bolaños et al., 2022)

PERFORMANCE REQUIREMENTS		
LOAD REQUIREMENTS	TRANSPARENCY	ABRASION RESISTANCE
		
While the 3DP4R guide does not offer a range on expected forces, as these can vary depending on the components and material use, 3D HUBS (2017) provides specific values such as LOW (<30 MPa), MED (30-85 MPa) and HIGH (>85 MPa). These specific thresholds facilitate aligning components with company requirements and protocols.	Transparent materials are limited to a few AM processes (SLA preferably). Note that SLS does not offer this material printing, implying that transparent components will require to be either redesigned or printed in alternative AM technologies.	Components in moving assemblies may suffer increased friction from the ribbed and rough surface, resulting in diminished part strength and durability. Components subjected to abrasion may necessitate additional post-processing to withstand heat and material erosion.
SURFACE SMOOTHNESS	FLEXIBILITY	
		
AM technology's surface finish quality, especially SLS, can be rough and ribbed by the layering nature of the process. Components needing smooth surfaces will require post-processing to achieve the desired finish. Leading to extended time and cost.	SLS technology at the company is limited to a single flexible material (TPU), constraining its use for a possible boarded range of flexible materials in products. While other flexible materials are available, these are restricted to alternative SLS printers.	

2.4. Defining criteria for spare parts suitability

Unlike self-repair operations, where users conduct DIY printing and repair activities, this thesis explores the company perspectives of AM for spare parts. Companies are subjected to additional factors such as supply chain challenges. Table 5 provides an overview of the criteria selected from the literature review (full table on Appendix D) following consultation with company experts based on the available documents at the company. Contrary to printability assessment criteria, the conducted literature review does not present a defined universal criterion for spare parts eligibility evaluation for AM. Each research paper focuses on different company objectives and author preferences (e.g., reduce lead times, reduce the cost of transportation, etc.) (Rao, 2021; Chaudhuri et al., 2019; Svensson et al., 2017; Knofius et al., 2016; Cardeal et al., 2020).

Table 5: Overview of listed attributes used by multiple authors when assessing spare parts suitability for AM manufacturing.

	DESCRIPTION	IMPLICATION	AUTHORS
PART COST	The cost of components can be a derivation from: -Manufacturing cost: Lower batches, manufacturing process ceased and complex geometries among others. -Shipping and logistics: Long distances between manufacturer and clients can increase the cost of parts.	AM manufacturing is inherently more expensive than traditional manufacturing processes (e.g., Injection Moulding) for large batch manufacturing. AM printing requires parts to hold higher value to be profitable (Holmström et al., 2010). The intrinsic cost-efficiency of AM lies in the reduction of logistics, complex part manufacturing and low-demand components. Factors that can present higher benefit from AM printing.	Cardeal et al., (2020), Knofius et al., (2016), Yesilkayali (2020), Holmström et al., (2010)
MINIMUM STOCK UNITS (SKU)	With AM, it is possible to produce parts on demand, reducing the need for low volume required stock units. Reducing the stocking cost, unused spare occupation and possible obsolescence of components stored for an extended period (Walter et al., 2004).	Components characterized by lower minimum SKU present higher suitability and benefit for AM production instead of keeping them in stock. Furthermore, these components can be integrated into a digitalised stock library, liberating storage space for more crucial components.	Everett, 2021; Ford et al., 2015; Varona et al., 2020
DEMAN VOLUME	AM cost-effective for small-batch production relative to traditional methods, due to their expensive tooling such as moulds (Sasson & Johnson, 2016). Large batch manufacturing can be challenging given the cost competitiveness of traditional manufacturing (IM) and the comparatively slower build speeds of AM technologies (Khajavi et al., 2014; Berman, 2012).	By understanding the demand volume of components, AM suitability can be assessed. High demand volumes can present a challenge, while lower demand and, especially out-of-stock components, can present higher opportunity for AM printing.	Knofius et al., (2016), Gibson et al. (2010), Yesilkayali (2020)

2.5. Priority components for repair

One of the main goals of the proposed eligibility framework is to identify and prioritize components that present higher relevance for repair activities. This way, companies can focus their attention on printing and redesigning, if necessary, these components first, and subsequent attention can be directed towards the remaining components. This ensures focus on components crucial for product longevity, optimizing resources and time. Three main criteria can be defined:

Functional importance

Functional importance parts contribute directly to the products performance (Fiorineschi et al., 2015). They can be grouped as primary, secondary, and lower importance based on their function (Terzioğlu, 2020).

Failure frequency

Foreseen number of times that a component fails in a specified period (ThePD, 2015) The understanding of these components could bring insights into the criteria for the future selection and evaluation of components to be fabricated with AM technologies. Due to confidentiality, the exact rates of the components will not be shared in the research.

Economic considerations

Economic factors influence users repair decisions as elevated prices can make users discard repair solutions for other alternatives such as acquiring new products (De Fazio, 2019; Cordella et al., 2019)

Additional consideration: availability as standalone spare part

Although not considered in the priority parts criteria, Terzioğlu (2022) and Buijserd (2022) mention the relevance of individual components as spare parts rather than assemblies. Buijserd's (2022) research into a Dyson product found that many components are not available as standalone spare parts as companies tend to promote the replacement of entire sub-assemblies. While this approach eases the replacement process for users, increases the cost and the number of unwanted components, and thus the sustainability impact of the repair operation. AM offers an opportunity to deliver only the required components, facilitating the repair activities.

2.6. Conclusion

The chapter presents the results from the conducted literature review aimed at identifying the criteria used to determine the eligibility of components to be AM printed as spare parts in the context of a commercial perspective rather than a self-repair scenario. The research explored three principal areas: Priority for repair, Printability, and AM for spare parts manufacturing.

2.6.1. Printability

Derived from TU Delft proposed 3DP4R Guide (Bolaños et al., 2022). Despite based on FDM technologies, it offers an overview of factors and considerations when analysing, printing and redesigning components for AM.

Part geometry criteria:

- Part Fit Requirement: Considering the space needed for parts connection and the precision of the technology.
- Number of Features: Understanding the number of distinct features in a component, which can contribute to manufacturing complexity.
- Shape Complexity: Simpler geometries are easier to print, post-process, and potentially redesign, while more complex shapes can present challenges in these aspects.
- Cavities: Cavities can cause excess material accumulation, posing challenges in post-processing and creating potential weak points in the structure.
- Fine Details: Small details can present to be a challenge for the precision of the AM technology, while their resolution can be affected by post-processes such as sanding.

Performance requirements

- Load requirements: Evaluation of anticipated part strength based on the expected loads it will sustain.
- Transparency: SLS does not present transparent materials, while these can still be printed in SLS, their functionality may be hampered.
- Abrasion resistance: Components exposed to mechanical wear and tear. It can be present in moving assemblies or components aimed to protect the product form possible impacts.
- Surface smoothness: Certain parts, especially those involving moving assemblies require of smooth surfaces. SLS textured and grainy finish will require post-processing, adding complexity, time and cost to the process.
- Flexibility: The reference printer (Formlabs Fuse 1+ 30W) available at company only offers TPU as a flexible material, limiting the technology's versatility.

2.6.2. Priority for repair

- Functional importance: Parts that contribute directly to product functionality.
- Failure frequency: Components that present a higher failure rate require of higher company responsiveness to assure the availability of spare parts for these cases.
- Economic considerations: Economic factors influence users repair decisions as elevated prices can make users discard repair solutions for other alternatives such as acquiring new products.
- Availability as standalone spare part: Access to spare parts may only come as part of an assembly, leading to the increase of cost and additional waste.

2.6.3. Spare parts suitability

As this project is undertaken with a particular focus on the perspective of OEMs and corporate entities, supply chain factors need to be considered:

- Part cost: The higher the part cost, the most suitable it is for AM production due to its inherent higher cost per part than IM manufacturing processes.
- Minimum stock keeping units (SKU): AM can reduce physical components stockpiling cutting cost and environmental impact. Lower SKU values can represent those components in less demand, therefore being more feasible for inclusion in a digital library.
- Demand volume: AM is not suitable for high-demand environments due its slower production rate. Yet, it excels in low-demand scenarios, especially for older products when production line may be halted.

3. Building the framework

3.1. Introduction

This chapter introduces the eligibility evaluation framework, which is based on the criteria identified in the literature review. Additionally, further literature research is conducted to better define the steps, processes, and activities within the process. It is important to emphasise that the goal is not to eliminate components, but to highlight the components more suitable to be AM printed for spare parts, with a focus on priority for repair.

The proposed framework is divided into three distinct phases: Cut-off criterion, Eligibility evaluation and Part selection. These stages collectively address the core research question:

MRQ: How can components eligibility be assessed?

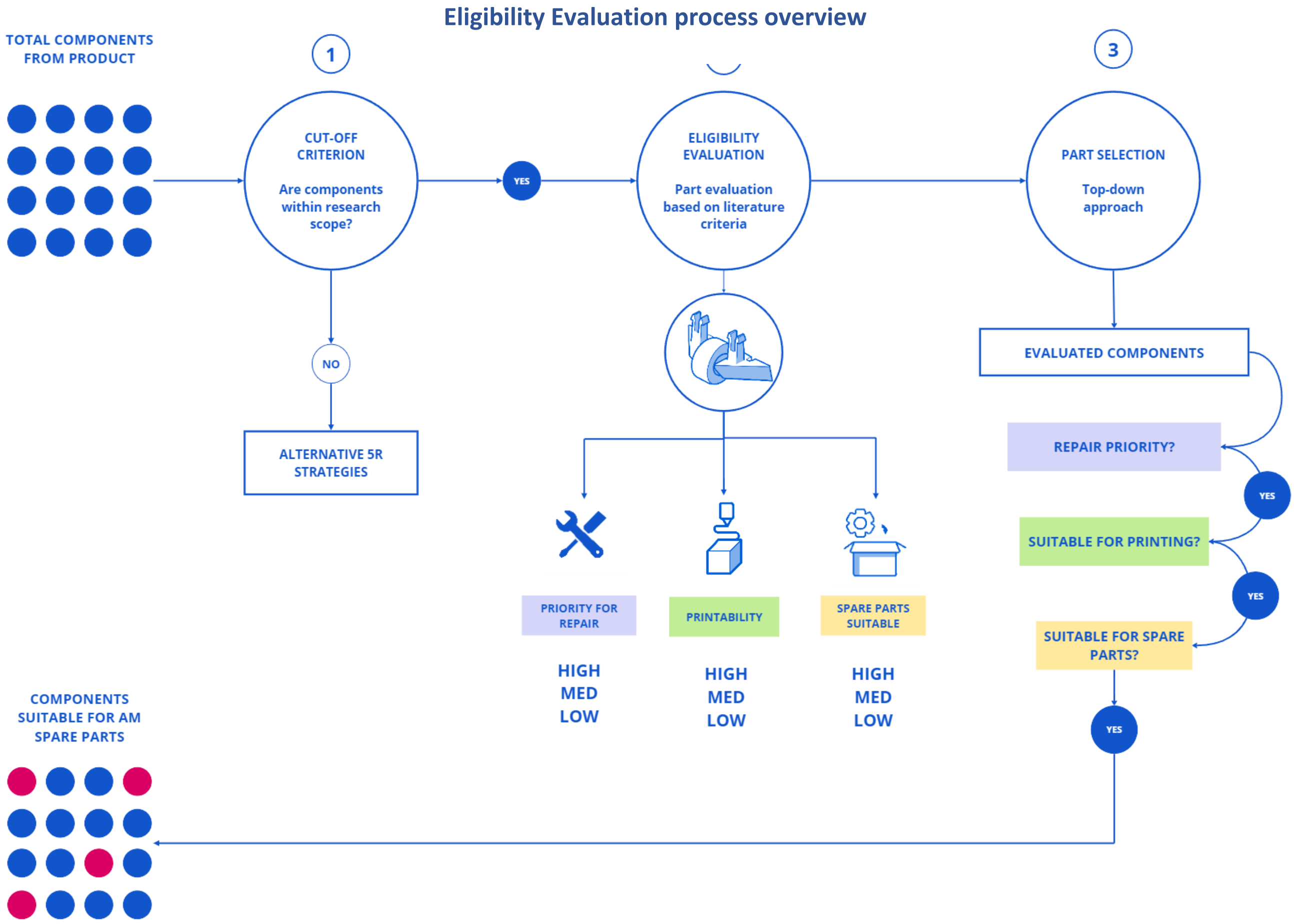


Figure 10: Overview of process

3.2. Step 1: Cut-off criterion

The Cut-Off criterion aims to discard components in a product that are unsuitable for AM printing. Following the proposed model by Cardeal et al. (2022), three groups are defined: standardized components (e.g., screws), which are not economically feasible for AM production; intellectual property (IP) protected parts; unsuitable printed by suppliers without company and OEMs approval; actuators (motors, pumps) or electronics, as they are not currently possible to be SLS printed. Every component identified that is part of one of these groups is labelled as NO-GO.

It must be noted that the goal of the Cut-off criteria is not to discard full assemblies, but specific components withing those groups. For example, while the motor is not suitable for SLS printing, its polymer frame can be potentially printed.

3.3. Step 2: Eligibility Evaluation framework

Figure 11 presents the proposed framework based on a weighted criteria matrix, where each case is evaluated according to the established criteria. To construct the framework, a Google spreadsheet serves as the foundational tool. It allows conducting automatic processes, including statistical analysis (e.g., mean, trend), logical functions (IF) and percentiles calculations, which will be in the upcoming section.

Weighting the criteria- Aimed at highlighting AM opportunities and suitable conditions.

The criteria derived from the literature review lack universal weighting, as each author is focused on company objectives or their own interpretations of the criteria. For instance, for priority components, De Fazio (2019) assigns scores to specific components based on their expected failure rate (some cases are motors=3, batteries=3 and wheels =1).

In the case of printability, Buijserd (2022) conducts a binary (Yes/No) approach for the printing factors listed in the 3DP4R Guide. While being a more straightforward proposal, it does not provide a precise overview of the components' complexity. For spare parts suitability, weighting through the Analytical Hierarchy Process (AHP) according to company objectives (Knofius et al., 2016; Rao, 2021) is omitted, as the objective is to provide a general solution applicable to a broader range of users in their respective assessments.

Therefore, the defined thresholds and weights are conducted on three main principles based on the identified cases: binary results, numerical values, and 3DP4R Guide illustrated ranges.

1. Binary results (Yes/No): For criterion lacking specific values. For example, transparency of parts. Yes =0, as SLS lacks that option, while No =1, being the most favourable condition.

2. HIGH, MED, LOW: Criterion that presents exact numerical values (e.g., demand volume or repair activities) are scored following three percentiles: $P_{25\%}$ (Low) $P_{50\%}$ (Med) and $P_{75\%}$(High). Percentiles are selected as they allow to categorize raw data in three simple thresholds (W3schools, Statistics - Quartiles and Percentiles).

Threshold values vary between 0 (Low) and 2 (High), except for the frequency of failure evaluation. Following Cordella et al.'s (2019) approach, higher failure rates have a substantial impact on the spare parts availability requirements as well as company responsiveness. Therefore, for this criterion, High is assigned a value of 3 to emphasize the significance.

3. 3DP4R Guide: For scenarios where, illustrated ranges are present (e.g., geometry complexity, shape complexity) the scores will reflect the position of the parts in the range. For example, the part shape complexity can be ranked from Flat (5) to Free organic (1), with the higher score indicating the most suitable scenario for printing. For cases where a specific range is not provided, these are scored based on Yes/ No.

4. Final scores: After the competition of the eligibility evaluation, the resulting scores are also classified as High, Med and Low. However, in this scenario, no percentiles are selected but a grading system: No-Go (0), referring to components within cut-off criteria, Low (1-4.99), Med (5-7.99), High (8-10).

This process follows a structure akin to the ABC method used by companies to prioritize components based on their annual consumption and inventory items (e.g., A represent companies 70-80% of yearly sales while representing only 20% of total inventory) (Acharya, 2021). As noted by Svensson et al., (2017), this scoring structure is widely recognized by companies, making it more accessible as they are more familiar with the concept, thereby enhancing its understanding.

3.3.1. Eligibility evaluation framework structure

1.Product description: The section gathers the description of the components within the product, the main assembly, material, and category. This can be used to identify out-of-scope parts (Cut-Off criterion) such as motors or PCB, which are then highlighted in red.

2.Replacemen availability: Assess component availability as spare parts and whether they can be acquired individually or only as assemblies (Priority for Repair: Standalone spare part criterion).

3.Elegibility evaluation criteria: The evaluation compromises three main areas: Printability, Spare Parts suitability, and Priority for Repair. Each component is assessed against the defined criteria and weighted accordingly.

4.Elegibility score: Process concludes by determining the Eligibility Score. Each area's criterion score is sum up and converted into a scale of 10 points. Based on the predefined thresholds for High, Med, and Low, the final scores are obtained.

PRODUCT DESCRIPTION						REPLACEMENT AVAILABILITY		PRINTABILITY					
ASSEMBLY	NAME	NUMBER	MATERIAL	CATEGORY	WEIGHT (gr)	AVAILABILITY	COST OFFICIAL (€)	PART FIT REQUIREMENT	COMPLEXITY OF FORM	COMPLEX CAVITIES	DIFFICULTY GEOMETRY	STRENGTH	FLEXIBLE
CHASIS	COMPONENT 1	1	TPE	PLASTIC	100	YES, AS ASSEMBLY	20	INTERFERENCE FIT	DOUBLE CURVED	YES	2-MAIN BODY + FEATURES	LOW< 30 MPA	YES
	COMPONENT 2	1	POM	PLASTIC	50	YES, INDIVIDUAL	10	NORMAL FIT	FLAT	NO	3-MAIN BODY ++FEATURES	MED 30 -85	NO
	COMPONENT 3	1	ABS	PLASTIC	70	YES, INDIVIDUAL	100	PRESS FIT	FREEFORM ORGANIC	YES	5-MAIN BODY,ADDITIONALL BODY + SEVERAL	HIGH >85 MPA	NO
	COMPONENT 4	1	Motor	motor									
	COMPONENT 5	2	PCB	PCB									

PRINTABILITY CRITERIA WEIGHT

CRITERIA	VALUES	WEIGHT
PART FIT REQUIREMENT	MOVING PART	3
	NORMAL FIT	2
	PRESS FIT	1
	INTERFERENCE FIT	0
COMPLEXITY OF FORM	FLAT	5
	SIMPLE GEOMETRY	4
	CURVED	3
	DOUBLE CURVED	2
	FREEFORM ORGANIC	1
DIFFICULTY GEOMETRY	1-SINGLE BODY	5
	2-MAIN BODY + FEATURES	4
	3-MAIN BODY ++FEATURES	3
	4-MAIN BODY, SEVERAL FEATURES	2
	5-MAIN BODY,ADDITIONALLBODY + SEVERAL FEATURES	1

CRITERIA	VALUES
STRENGTH	LOW < 30 MP
	MED 30 -85
	HIGH>85 MPA
FLEXIBLE	YES
	NO
COMPLEX CAVITIES	YES
	NO
TRANSPARENT	YES
	NO
FINE DETAILS	YES
	NO
SMOOTH SURFACE	YES
	NO
ABRASION	YES
	NO

Figure 11: Structure of Eligibility Evaluation framework. The examples do not reflect any of the company's real components data; they are mere illustrative.

				SPARE PARTS SUITABILITY						PRIORITY					ELIGIBILITY SCORE		
ASION	TRANSPARENT	SMOOTH SURFACE	FINE DETAILS	VOLUME UNITS	VOLUME	PART COST UNITS	PART COST	MIN SKU UNITS	MIN STOCK LEVEL	STANDALONE SPARE PART	FUNCTIONAL IMPORTANCE	FREQUENCY OF FAILURE	FREQUENCY OF FAILURE	COST OF REPLACEMENT	AM FOR PRINTING	PRIORITY	AM FOR SPARE PART
	NO	YES	NO	200	HIGH	0	LOW	100	HIGH	NO	HIGH	100	HIGH	MED	HIGH	HIGH	LOW
	NO	YES	NO	50	MED	10	MED	15	MED	YES	LOW	15	MED	LOW	MED	LOW	MED
	NO	YES	YES	20	LOW	66	HIGH	5	LOW	NO	MED	5	LOW	HIGH	LOW	MED	HIGH

EIGHT
3
2
1
0
1
0
1
0
1
0
1
0
1
0
1

SPARE PARTS SUITABILITY WEIGHT

CRITERIA	VALUES	WEIGHT	UNITS-VALUES	PERCENTILE
DEMAND VOLUME	HIGH	0	HIGH	75th percentile
	MED	1	MED	50th percentile
	LOW	2	LOW	25th percentile
PART COST	HIGH	2		
	MED	1		
	LOW	0		
MIN SKU	HIGH	0		
	MED	1		
	LOW	2		

PRIORITY CRITERIA WEIGHT

CRITERIA	VALUES	WEIGHT	UNITS-VALUES	PERCENTILE
STANDALONE SPARE PART	YES	0	HIGH	75th percentile
	NO	1	MED	50th percentile
FUNCTIONAL IMPORTANCE	HIGH	2	LOW	25th percentile
	MED	1		
	LOW	0		
FREQUENCY OF FAILURE	HIGH	3		
	MED	1		
	LOW	0		
COST OF REPLACEMENT	HIGH	2		
	MED	1		
	LOW	0		

3.4. Step 3: Component selection process

Following Knofius et al. (2016) proposed top-down approach, components are systematically narrowed down from an initial pool. This method proves advantageous when handling extensive inventories, aiming to prioritize components to be printed, tested, redesigned if needed and implemented for commercial use (Chaudhuri et al., 2019).

Figure 12 outlines the selection process. Only components scoring HIGH and MED are considered. This decision is made with the objective of assessing the printability of various components with distinct scoring. Alternatively, only HIGH scoring components can be selected for further narrow results.

The process begins with the selection of priority for repair components from the initial in-scope pool. From this selection, components suitable for AM printing are further chosen. Subsequently, the focus narrowed to those deemed suitable as spare parts.

The sequence embodies the framework objective; to prioritize valuable components for repair activities. Consequently, only components with value for repair are first printed and tested, with the remaining components served for future s.

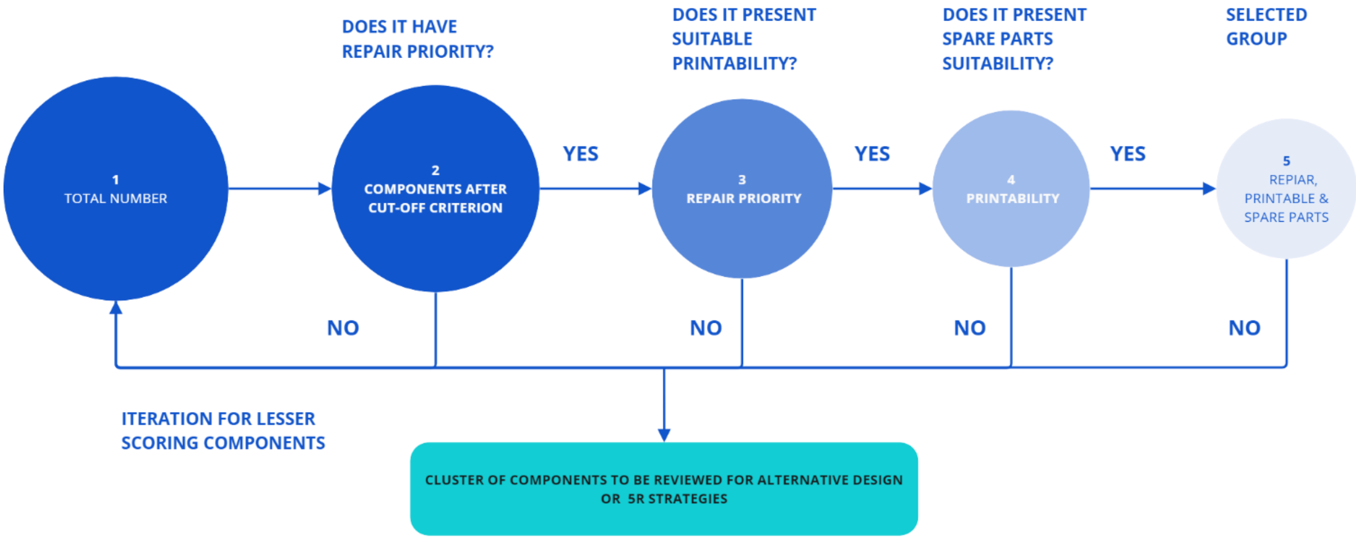


Figure 12: Overview of the conducted screening steps to select components eligible for AM spare parts.

3.5. Conclusion

The proposed framework integrates research insights from TU Delft into the eligibility of components to be AM printed (Bolaños et al., 2022; Buijserd, 2022), the identification of the key components for repair (Flipsen et al.,2020; EN 45554, 2020) and opportunities for AM in spare parts manufacturing (Rao, 2021; Chaudhuri et al., 2019; Knofius et al., 2016 etc.).

The objective is to assess component suitability for AM production, enabling companies to focus their efforts on parts key for repair, eligible to be AM printed and best suited for spare parts attributes. The identified eligible components present the most suitability to be implemented in an AM digital library, as they can pass the three main filters:

1.Cut-Off criteria: This step aims to identify out-of-scope components, such as standardized components, and electronic and metal parts. These components are not economically or even feasible to be AM printed, therefore no eligibility evaluation will be conducted on them.

2. Eligibility evaluation: Components within the research scope undergo a systematic evaluation across the three main domains: Repair priority, Printability and Spare Parts suitability. These three areas of research provide companies with an overview of each component's attributes, facilitating the decision-making on appropriate strategies.

3. Component selection: Employing a top-down approach, components prioritized for repair activities are first selected, followed by the ones that present suitable printability, finalising those components within the previous group that present the best eligibility for the current supply chain and spare parts attributes.

The proposed framework will allow to identify which components from the company's proposed products offer eligibility as AM spare parts, while also presenting an opportunity for testing the selected technology at the start of the second part of the research project.

Part 3. Framework validation method

Introduction to part 3

In this chapter, the methodology used to validate the framework is presented. Currently, the proposed framework is based on literature review insights and discussed criteria with the company. To evaluate its effectiveness and knowledge gaps, a practical study is conducted by simulating the full process companies are expected to conduct, from product research, and eligibility evaluation to print and redesign proposals. For that, the process is divided into three main steps: Step 1. Product Research, Step 2. Eligibility Evaluation, Step 3. Print and test.

The insights gathered through the process are presented in Part 41. Step 1: Product research

1. Step 1: Product research

1.1. Introduction

A Product Breakdown Structure (PBS) is conducted to achieve several key objectives. Identify the total count of components and materials, identify out-of-scope components, pinpoint functional relevant components, reveal component relationships and highlight any phenomena that could influence parts' printability.

1.2. Product selection

The proposed products by the company are the SpeedPro (SP) and SpeedPro Max (SPM). These products represent Philips' and Versuni's 'vacuum cleaners' portfolio. Since these products are soon to be discontinued, this scenario provides an opportunity for the company to investigate the utilization of AM for their current products.

1.3. Product Breakdown Structure activity

Collect product information

Conducting a priors disassembly process in conjunction with company experts allows to gather an understanding of the product structure, functionality, and identification of components critical for repair due to anticipated faults and their direct impact on product functionality.

Identify out-of-scope components

By combining the data form the BOM list and the insights form the disassembly process it is possible to identify possible out of -scope components, which will be later assessed during the cut-off criterion.

Highlight functional relevance components

As part of the upcoming eligibility evaluation, identifying functional relevant components will provide valuable guidance. The insights derived from the collected product information during the early disassembly process, combined with literature research will aid in the process.

Product Disassembly

The disassembly is conducted at TU Delft Applied Labs following the service manual provided by the company. Both products are disassembled and reassembled while insights on individual components or assemblies are noted down. The iFixit Manta Precision Bit Set is used for the disassembly while the process is recorded with side and top-view cameras. The gathered insights are discussed with the company expert.

Excluded parameters & activities

As previously mentioned, the goal does not involve assessing the products' disassembly process. Therefore, no time record is set for the process and no specific

Figure 13: Results from conducted disassembly process sin collaboration with company experts.

2. Step 2: Eligibility Evaluation

2.1. Introduction

Step 2 conducts the eligibility evaluation of both products based on the gathered insights from the conducted product research and company-gathered data. For this purpose, the 3 steps explained in Part 2 (section 3) are followed: step 1: cut-off criteria; step 2: eligibility evaluation; and step 3: component selection. By applying the framework to a case study, the defined research question is answered:

RQ.4: Which components from the proposed products present suitability for AM spare parts?

3. Step 3: Components' print and test

3.1. Introduction

Step 3 conducts the printing and testing of components selected from the previous section. The goal of the step is to assess SLS print performance compared to IM and understand implications in part performance and printability assessment. The testing follows the 3DP4R Guide proposed areas of research and specific criteria based on product category.

RQ.4 How does SLS printed components compare to the original ones?

3.2. Quality testing

Following proposed 3DP4R Guide print quality process, this section aims to evaluate how successful the printed components are and how they compare to the IM manufacturer components.

Visual testing

Evaluate if the printed components present the required geometry reproduction and surface quality. For that, side by side comparison of printed and original components is conducted, special observation given at the identified essential features.

Dimensional accuracy

Dimensional accuracy refers to the measure of printed components' reproduction of the original geometry dimensions, usually expressed as percentage or millimetres (Ye, 2021). For this evaluation, random sampling is conducted to select three printed components. General measures from essential features are obtained with a calliper and listed in a spreadsheet table. The average dimensional deviation from GF 12 and PA 12 printed components from the original CAD file is calculated.

SLS expected tolerance is ±0.3mm (3D Hubs, SLS design). Therefore, any registered dimension that surpass the value may indicate print failure such as warping or shrinkage.

3.3. Assembly testing

Fit requirements

The test evaluates if the fit requirements are met from SLS printed components. For that, the components are assembled and disassembled in the product.

General functional observation

An observation of the workings of the components within the product assembly. The goal is not to evaluate specific attributes of the parts, but to conduct a general overview of SLS printed components with original IM parts and highlight observed remarks. For that, first components are assembled and then at the company Home Lab (Simulation of an average living room) a simulated vacuuming session is conducted.

3.4. Specific attributes testing

In addition to the conducted qualitative observations, further specific testing is conducted to better understand SLS technology implications for specific case scenarios:

3.4.1. Airflow test: Vortex finder

Owing to the nature of the duct category, air data standard EN 60312-1: 2017, 5.8 is conducted to evaluate printed components performance in regards of airflow (L/s) and suction power(W).

Set-up

The product to be tested is connected to the measuring device, which cycles the size of several plates' aperture diameter to measure flow in distinct stages. The SPM is set at the TURBO mode to register the maximum capacity of the product.

Selected component

Company experts advised conducting the test with the Vortex finder. The component generates airflow (vortex) inside the dust bucket. This airflow separates heavy from light particles, being collected in the second and being filtered in the first chamber respectively. This component is essential for vacuum functionality, without it the product would not be able to effectively suction any particles.

Qualitative vacuuming test

The qualitative test aims to perform a side-by-side comparison of the printed Vortex finder and the original manufactured part in the vacuuming of a series of substances. These substances are used by the company to observe the behaviour of the product when vacuuming different particles. This aims to represent everyday scenarios. Table 66 presents an overview of the used particles.

The test is conducted by spreading the particles on a flat surface, which will be vacuumed using exclusively the main body without a nozzle and tube to reduce additional variations. The SPM is set at TURBO during the activity. The observed results are compared to the original vortex finder and assessed.

3.4.2. Load test

Components deemed of relevance for repair and expected to endure substantial loads are tested to evaluate the strength comparative between SLS and IM components. The test protocol involves defining the use scenario and assumed failure points in the part essential features.

By means of a digital force gauge and stress-strain test equipment at TU Delft Applied Labs, the aim is to ascertain the components' failure points, assess damages and evaluate design solutions that can enhance part strength.

3.4.3. Flexible components

To assess SLS viability for flexible part printing, identified flexible components within a product are printed. The evaluation of these components will follow a general overview of their print quality and a side-by-side comparison with originals in degree of flexibility and fit requirement.

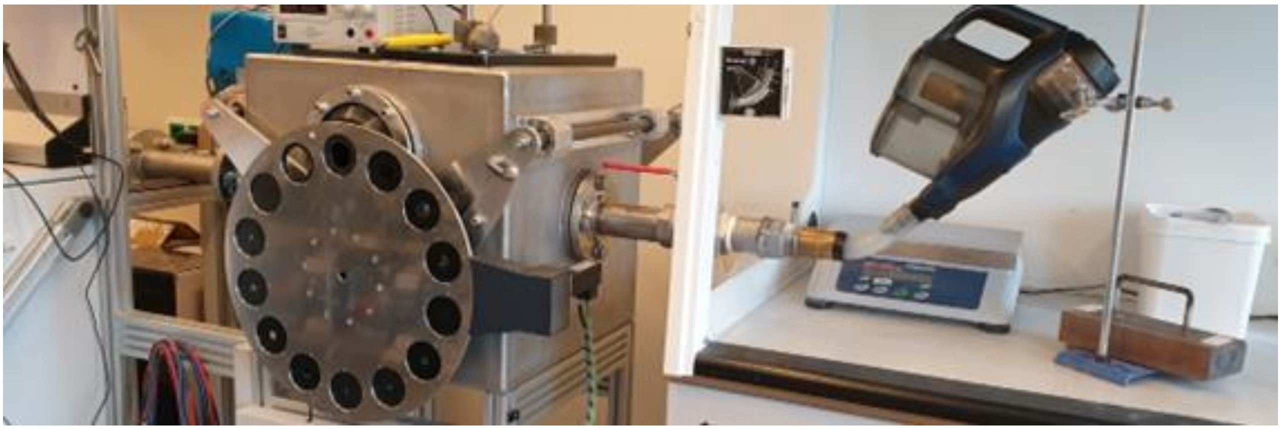


Figure 14: Airflow test setup, where the SPM is connected to the measuring system.

Table 6: Overview of selected substances to evaluate printed Vortex finder performance compared to original part.

		
Substance 1: Use of lentils to similar vacuuming of solid debris like smaller rocks or dirt. The vortex is expected to separate this element into the second chamber.	**Substance 2:** Combination of lentils and rice for smaller particles, and synthetic hair.	**Substance 3.** Combination of previous substances with the addition of foam and powder to simulate dust. The printed components may be subjected to particles' adhesion owing to their rough surface.

3.5. Conclusion

The validation of the proposed framework follows the complete cycle expected to be conducted by designers at the company. The goal is to apply the defined framework to two proposed products by the company, the Philips SpeedPro (SP) and SpeedPro Max (SPM). There are three main steps:

Step 1: Product research. This step involves disassembling selected products to define their architecture, aiding in the identification of functional importance components, individual parts geometry requirements and parts that fall outside the research scope. Additionally, gathering company's documentation for upcoming eligibility evaluation (after-sales data, repair activities, CAD files). This process serves as the foundation for the forthcoming eligibility evaluation.

Step 2: Eligibility Evaluation. The second step applies the eligibility framework to assess the component's suitability for AM printing as spare parts. This process involved an initial Cut-off criterion to identify and discard components falling outside the research scope. Followed by the criteria derived from the conducted literature research encompassing Printability, Repair priority and Spare Parts suitability. Finally, the selection of the components for the upcoming printing and testing is conducted based on the proposed layered process, and prioritization of the key components for repair activities.

Step 3: Components Print and Test. Based on the activities proposed by the 3DP4R Guide, the print and test of components are conducted in the following areas: Print quality (surface finish, dimensional deviations, details), Fit requirements, Performance test and Specific attributes test (Airflow, part strength, flexible components). The aim is to gain a thorough understanding of SLS-printed components and compare their performance to their original IM counterparts.

This process will serve to identify gaps in the eligibility framework and a deeper understanding of SLS printing components compared to the originally IM manufactured parts.

Part 4. Validation results

1. Step1: Product research results

1.1. Introduction

This section presents the results of the conducted Product Research. First, the product disassembly is conducted, assisted by the documentation gathered from the company. Following with the product architecture mapping. The gathered insights will assist in the upcoming eligibility evaluation.

1.2. Product Breakdown Structure

Figure 16 presents the general architecture of the product. Both components share a similar structure divided into three main groups and a total of 13 sub-assemblies. The provided BOM list of both products presents a total of 341 individual components.

Notably, due to their sharer design similarities, both products offer the potential for interchangeability between the tube and nozzle components. This possibility implies that if a solution is achieved in components within these assemblies, it can be a solution for both products, being a clear opportunity.

Figure 15 presents the distribution of number of components per materials type. Interestingly, ABS happens to be de predominant polymer, followed by POM and PP.

In total, 14 different polymer materials are present in both components. Discussing the implications of the material diversity with the company Lead Engineer, the conclusion is that it presents a challenge for SLS as it will be hard for the technology not only to match the same number of materials but also their individual properties. This can be further evaluated with the upcoming printing and testing of components with their original counterparts.

1.2.1. Functional importance components

The connected Product Breakdown structure presents the overview of identified components of functional importance and frequency of failure based on discussions conducted with company engineers and a literature review (Fonteijne 2021; Rames et al., 2018), indicated with a gear icon.

As part of the upcoming eligibility evaluation, this activity serves to identify the range of functional priority of components, as it is not specified in company procured documents.

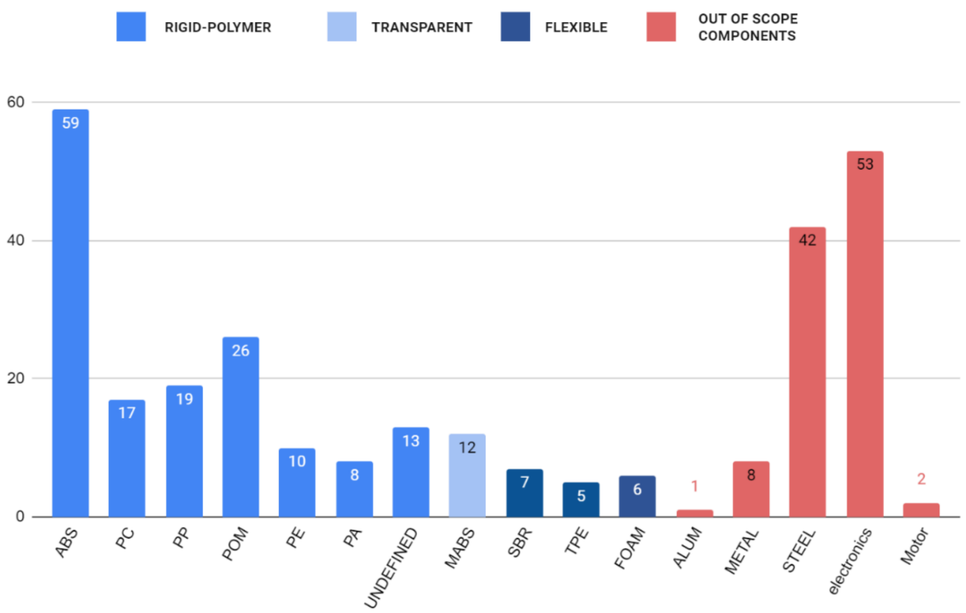


Figure 15: Overview of the number of components per material type present in both products assemblies.

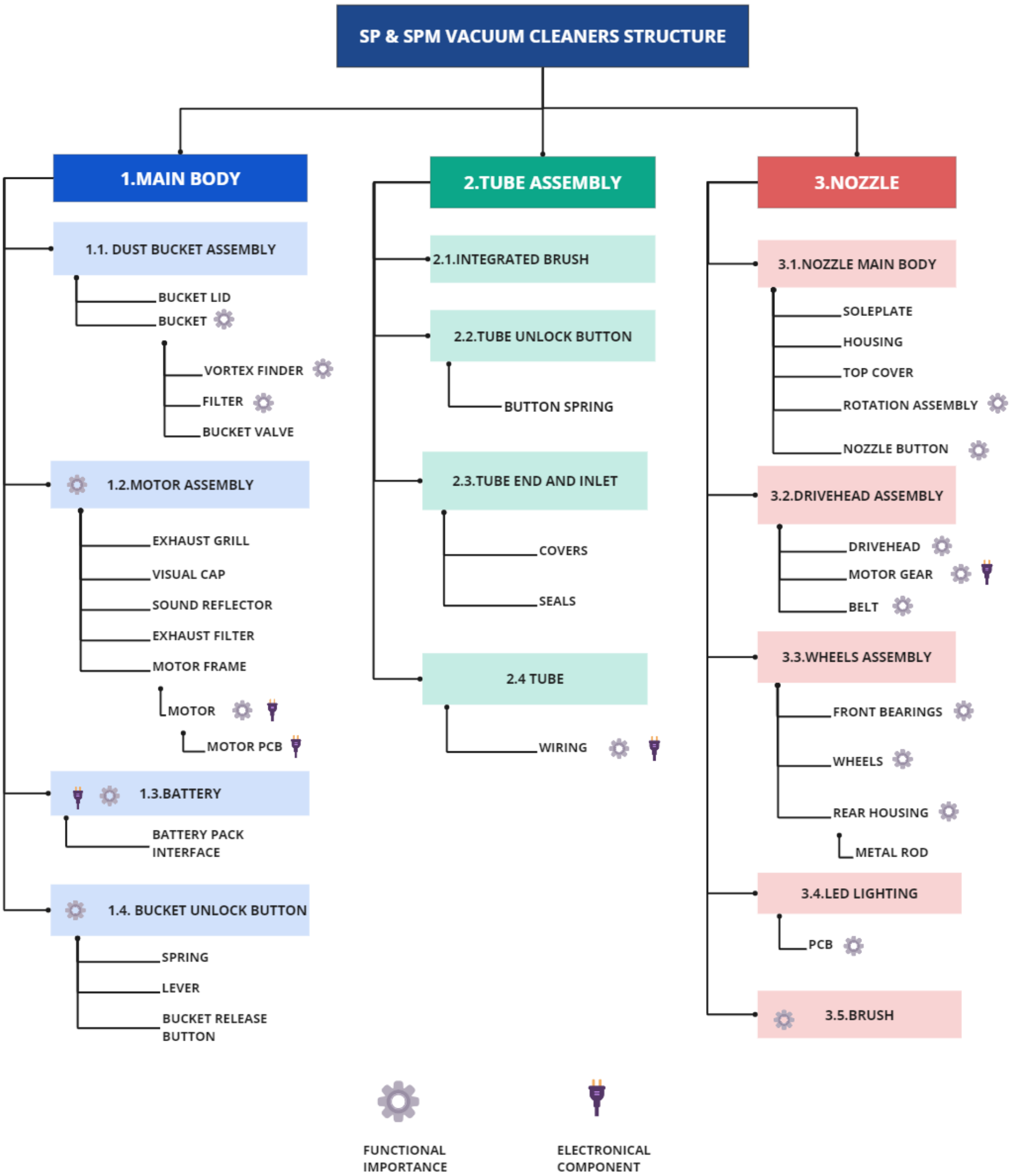


Figure 16: Overview of product architecture and early identified electronical components, being out of scope.

1.3. Insights from disassembly process

1.3.1. Components complexity

The conducted disassembly activity provides insights into component complexity, aiding in a better understanding of the criteria outlined in the 3DP4R Guide.

Highly complex components can be exemplified by the chassis and the nozzle soleplate, which serve as the core of the respective assemblies. Their numerous snap fits and features serve as fit solutions for 78 and 63 individual components, respectively. This results in an intricate geometry with several cavities, that can lead to a challenging AM printing process, as any slight dimensional deviation or print failure (e.g., warping or shrinkage) can lead to an assembly failure.

In contrast, components like the slider, tube buttons and brush drivehead represent simpler geometries, primarily owing to their flat surfaces and fewer features, making the best suited for AM printing.

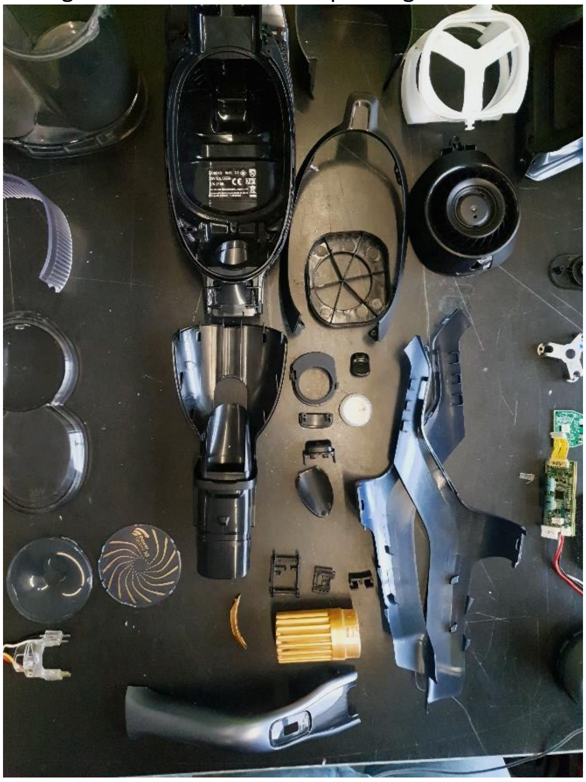


Figure 17: Resulting disassembly process and variety of components in size and complexities.

1.3.2. Multi-material components

The disassembly process revealed the presence of multi-material components, referring to parts which present two or more distinctive materials irreversible joined together. Five such components were identified, including the SPM Handheld cover, front and rear wheels, and the Nozzle soleplate (see Figure 18). These components are manufactured using a 2K injection moulding process (Xometry, 2022).

These components present a challenge for SLS technology, as currently, no such manufacturing process is possible. Additionally, the 3DP4R Guide does not consider multi-material as a factor, but it can be understood that they can pose a challenge. Even if individual parts within a multi-material component can be printed effectively, their fit requirement may not be achieved, as their geometry is designed for the 2k process. Therefore, alternative design solutions are required, extending the company's efforts to ensure their printability.

Figure 18: Nozzle soleplate presenting blue over moulded flaps for enhanced particle collecting.

1.3.3. Flexible components & transparent components

A total of five flexible materials and twelve transparent materials are present in the products. For instance, the wheel tires, made of a rigid material (TPU), and product-specific bucket inlet seals, made of a softer material (SBR), highlight not only the diversity in material types but also their respective hardness characteristics.

The selected SLS printer as reference (Formlabs Fuse 1+30W), only offers one TPU powder and currently no transparent materials (Formlabs, official webstore). Alternative flexible materials, like TPE (softer material than TPU), may be only feasible to specific SLS printers, as is the case of SINTERIN TPE powder, compatible only with Lisa and Lisa Pro printers (SINTERIN, TPE). As a result, alternative printers and technologies might be necessary to support SLS in such scenarios.

In regards of identified transparent components, counting a total of 12 components such as the nozzle window and dust bucket, which require transparency for functionality.

Figure 19: (Top) Motor suspension rubber made from SBR. Its high flexibility allows to mitigate motor vibrations to the rest of the body. (Bottom) Transparent UI window over moulded in the handheld cover.

1.3.4. Damaged components

During the disassembly process, some components presented damaged snap-fit features, making it impossible to be re-assembled back in place.

The side panels and the handheld panels' snap-fit solution are some of the examples (see Figure 19). The main cause is the multiple orientation in which the components snap-fits connect to other parts. Multiple-direction snap-fits can complicate the disassembly as is harder to identify the correct orientation for each connection, potentially leading to confusion, excessive force application, and component damage.

1.4. Spare parts availability

The results from the conducted research reveal that while certain parts such as the Vortex finder and integrated brush are available individually, most components are only available within assemblies. For example, the wheel for the nozzle is not sold separately, rendering users and unofficial repair centres to purchase the whole assembly for € 60 (Philips official store). Other cases are the side panels and the handle cover, identified as broken during the disassembly process, for which the official website only offers a full body replacement (150 (SP) to € 200 (SPM). This might also indicate the process of both components being discontinued, the full list is available in Appendix

Figure 20: Close up on the damaged snap-fits of the handle cover.

1.5. Conclusion

The product research step serves as the foundation for understanding both the intricacies of the product and the attributes of the individual components within. The conducted product structure study helped identify the functional relevance components and out-of-scope elements. Additionally, the gathered documents (e.g., BOM list, CAD files, and Service manual among others) will serve in the upcoming eligibility evaluation step.

In total, both products contain 341 individual components, a total of 14 rigid polymers, five flexible and 12 transparent materials are identified. This wide range of components and material types presents a challenge for SLS due to its limited material range of five rigid polymers and one flexible material, using the printer at the office as a reference (Formlabs Fuse 1+30W). The volume of components in two products highlights the challenge companies face when classifying and managing their product portfolio components pool. The proposed eligibility evaluation streamlines company efforts toward key components for product repair and AM spare parts.

The research also shows the limited number of components available as individual spare parts. Coupled with the observed failure of certain components' snap-fits during disassembly, underscores the implications for repairability of products and their direct sustainability impact. The observed failures are recorded in components with no available replacements for the public, and instead, complete assemblies are required to be purchased by users. This underlines one of the major advantages of AM, the manufacturing of individual spare parts for costly or inaccessible components.

2. Step: Eligibility evaluation results

2.1. Introduction

This section presents the results conducted from the Eligibility Evaluation framework. Due to the confidentiality of the data gathered for AM for Repair and Spare parts, the specific values (e.g., number of parts sold, number of repair activities, minimum stock-keeping units (SKU), etc.) are not discussed.

2.2. Cut-off criteria results

The resulting Cut-Off criteria identify 207 components (24 discarded as the parts are deemed out of scope and not due to AM printing impossibility) deemed to be discarded, with 135 components within the scope (see Figure 21:). These results present that only 39.30 % of components from the total (SP and SPM combined) can be AM printed within the scope of the research. This presents a limitation of AM to cover every component within a product, leading companies to explore alternative sustainable solutions for those unselected components (e.g., remanufacturing, reducing, repurposing, etc.).

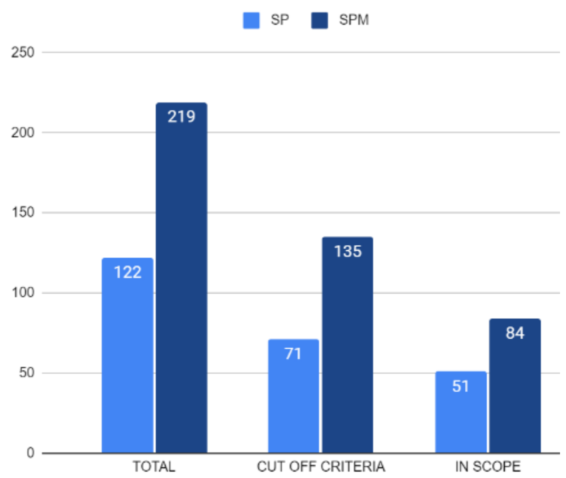


Figure 21: SP and SPM Cut- Off criteria results.

2.3. Eligibility evaluation

Figure 22: the acquired scores from the eligibility evaluation framework. Notably, no High Repair Priority OR Spare Part suitability scores are achieved. This is observed to be a limitation of the gathered company's data analysis. Both the after-sales and registered repair activities data are provided at the assembly level, whereby the genuine values for the individual components cannot be assessed and their values are dependent on the group.

This approach hinders the precise component eligibility evaluation, resulting in accuracies such as the Vortex finder and Nozzle brush, which despite being of main functional importance among their respective assemblies, the scores are shared with other less relevant components.

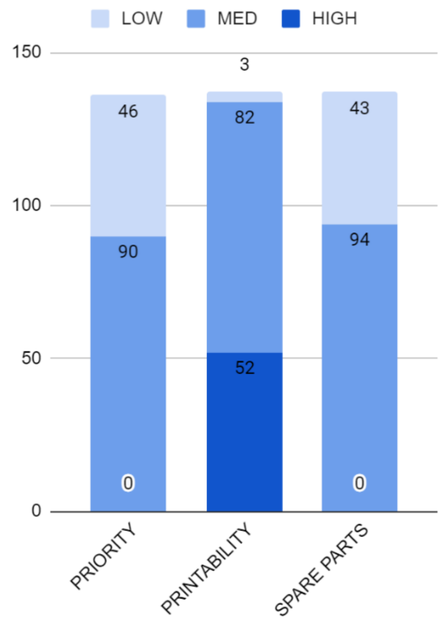


Figure 22: Results from conducted eligibility evaluation.

2.2.1. Printability scores

The results present 52 components to be highly suitable for AM printing, while three deemed low.

While conducting the eligibility evaluation, it becomes evident that there is a degree of subjectivity in part scoring. In contrast to binary criterion weighting (Yes/No), criteria with multiple categories can blur the boundaries between closely ranked categories, especially if these are not well-defined.

For instance, when assessing the geometry complexity, there is a challenge to effectively determine if a component belongs to the *Main Body-Additional features + several features* (score 1), *Main body -several features* (2 score) or Main *body ++ features* (3 score).

In these cases, size has been used as a determining factor. Larger parts' increased surface area can result in longer print time and might present greater potential for print failures due to uneven cooling of the component or incorrect layer adhesion (CEAD, Insights to prevent large-scale deformation).

Part volume can also serve as a quantitative criterion to balance the subjectiveness of the evaluation. Greater part volume results in more material usage, longer printing time, and higher environmental impact (Markfroged, Desing for 3D Printing; Tagliaferri et al., 2019). CAD software can accurately measure 3D models' volume. Although weight was initially considered, this criterion can vary significantly based on material density and properties: 0.95 g/cm^3 (PA 12), 1.22 g/cm^3 (GF 12) and 1.07 g/cm^3 (ABS) (Materialise, Materials).

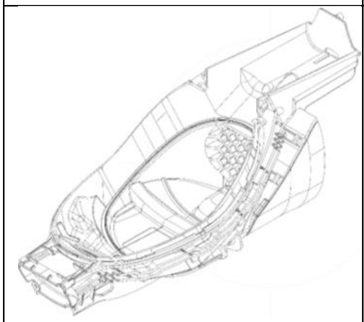
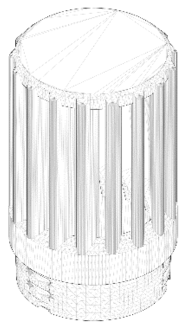
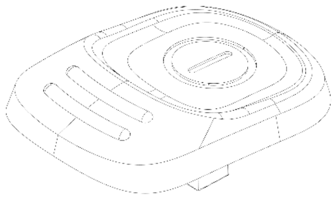
It is important to note that the evaluation of fit requirements reveals a notable limitation in cases where components may possess multiple requirements simultaneously. In such scenarios, the most challenging one is set. For example, the Tube end presents a press fit with an aluminium tube but a normal fit with the covers.

Table 7 illustrates the differences between High, Med, and Low printable components.

PART CLASSIFICATION ANDN													
ASSEMBLY	NAME	PART FIT REQUIREMENT	GEOMETRY										
			COMPLEXITY OF FORM	COMPLEX CAVITIES	DIFFICULTY GEOMETRY	FORM FIT	STRENGTH	FLEXIBLE (RUBBER,FOAM)	ABRASION	TRANSPARENT	SMOOTH SURFACE	FINE DETAILS
	sp.Bucket lid	PRESS FIT	SIMPLE GEOME	NO	2-MAIN BODY + FEATURES	HIGH < 0.3 MM	HIGH >85	NO	NO	YES	YES	YES
	Tampon print											
	sp.Bucket lid sealing	NORMAL FIT	SIMPLE GEOMETRY	NO	2-MAIN BODY + FEATURES	MED +- 0.3 MM	LOW< 30 MPA	YES	NO	NO	YES	NO
	sp.VORTEX CAP	PRESS FIT	SIMPLE GEOMETRY	NO	2-MAIN BODY + FEATURES	HIGH < 0.3 MM	LOW< 30 MPA	NO	NO	YES	YES	YES
ACTIVE NOZZLE	Assy ACTIVE nozzle											
	sp.SW passive nozzle soleplate incl Squeegee	PRESS FIT	CURVED	YES	4-MAIN BODY, SEVERAL FEATURES	HIGH < 0.3 MM	MED 30 -85	NO	NO	NO	NO	NO
	sp.SW passive nozzle Airchannel insert	PRESS FIT	DOUBLE CURVED	YES	4-MAIN BODY, SEVERAL FEATURES	HIGH < 0.3 MM	MED 30 -85	NO	NO	NO	NO	NO
	Squeegie											
	sp.Front Wheel Bearing	PRESS FIT	SIMPLE GEOMETRY	NO	2-MAIN BODY + FEATURES	HIGH < 0.3 MM	MED 30 -85	NO	YES	NO	NO	NO
	Front Wheel Axle (22,5x3mm)											
	sp.Front Wheel Base	NORMAL FIT	SIMPLE GEOMETRY	NO	2-MAIN BODY + FEATURES	MED +- 0.3 MM	MED 30 -85	NO	NO	NO	NO	NO
	sp.Front Wheel Over Mold	PRESS FIT	SIMPLE GEOMETRY	NO	1-SINGLE BODY	HIGH < 0.3 MM	MED 30 -85	YES	NO	NO	NO	NO

Figure 23: Section of conducted Printability evaluation.

Table 7: Overview of scoring examples of Low, Med, and High printability.

	CHASSIS		VORTEX FINDER		SWITCH	
DESCRIPTION	Product Research already identified the chassis as a challenging component due to its intricate geometry with multiple features and cavities. The resulting evaluation confirms the assumptions resulting in a LOW score.		Despite the presence of aerodynamic pillars and a series of hook-fit features, it is an achievable print. Regarding mechanical requirements, the component's smooth surface will surely require additional post-processing, leading to increased cost and time.		The slider does not present high performance requirements and the overall shape of the components is simple. However, the features and details on its upper face can present a challenge for the SLS printer and its accuracy.	
						
SCORING						
FIT REQUIREMENT	PRESS FIT	1	PRESS FIT	1	NORMAL FIT	2
FORM COMPLEXITY	DOUBLE CURVED	2	MAIN BODY ++FEATURES	3	SIMPLE GEOMETRY	4
COMPLEX CAVITIES	YES	0	NO	1	NO	1
GEOMETRY DIFFICULTY	MAIN BODY, ADDITIONALLBODY + SEVERAL FEATURES	1	MAIN BODY + FEATURES	4	MAIN BODY + FEATURES	4
STRENGTH	MED	2	LOW	3	LOW	3
FLEXIBLE	NO	1	NO	1	NO	1
ABRASION	YES	0	NO	1	NO	1
TRANSPARENT	NO	1	NO	1	NO	1
SMOOTH SURFACE	YES	0	YES	0	NO	1
FINE DETAILS	YES	0	YES	0	YES	0
FINAL SCORE	LOW	8/22	MED	15/22	HIGH	18/22

2.4. Component selection

Following the layered selection process explained in Part 2, section 3, the components are filtered based on the score. Only components with high and medium scores were selected. Consequently, 21 components of the total 341, can be categorized as suitable for AM spare parts, with the intent of printing, testing, and putting into service in a digitalised library. The components that have been not selected are not to be discarded, as the results from the total eligibility scores, several of them still present suitability for spare parts and printing.

2.4.1. Print and test component selection

The results of the eligibility evaluation are discussed with the company with the goal of prioritization of components for the upcoming printing and testing. The decision is made to include components from the Printability group as well, as these could offer further insight into the challenges for SLS spare parts printing.

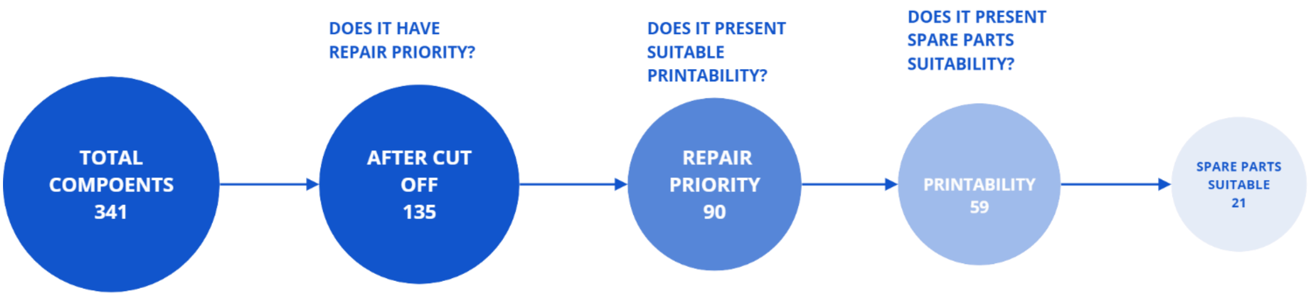
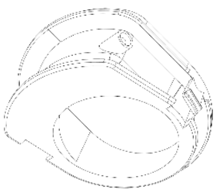
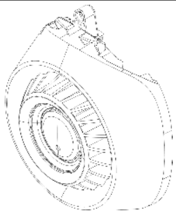
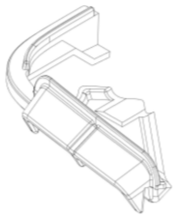
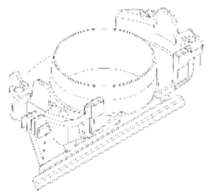
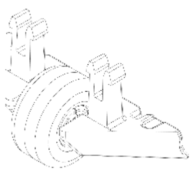
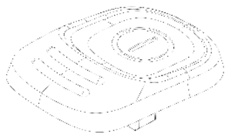
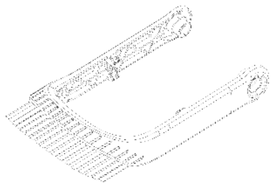
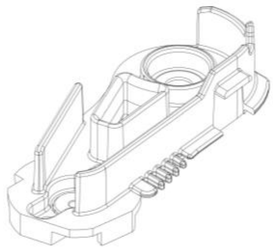
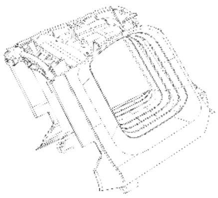
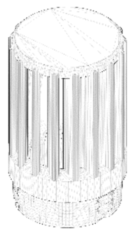
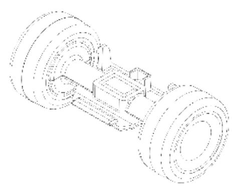


Figure 24: Illustration of the number of components and their percentage after each layer of selection. of the percentage of eligible parts compared to the total of the previous filtered group.

Table 8: Example of identified eligible components.

EXAMPLES			
			
			
			

2.5. Conclusions

The conducted Eligibility Evaluation framework in the proposed product study revealed the following main points:

1. Source data limitations & eligibility evaluation: The data provided by the company on repair activities and after-sales documentation is presented at the assembly level, therefore specific attributes for each component cannot be assessed. This leads to less relevant components for repair to have the same value as the potentially relevant component in the assembly. Similarly, in the scenario of demand, more suitable components can be influenced by the high demand for components within the assemblies.

2. Cut-Off criteria: The use of cut-off criteria based on BOM descriptions and material categorization successfully filtered out of scope components, from original 341 to 135 components.

3. Evaluation subjectivity: The eligibility evaluation exhibited subjectivity, particularly in the Printability evaluation, due to the lack of understanding of part requirements such as strength or press-fit, as no exact references could be identified in the company-provided data. Regarding fit requirement criteria, some components have multiple contact points with other components, each with its unique fit requirement. In such cases, the more complex fit requirement is selected, which might not represent the overall complexity of the part.

Regarding part complexity, where no clear boundary is sent between Main Body-Additional features + several features (score 1), Main body -several features (2 score) or Main body ++ features (3 score), the overall dimension of the part is considered. Larger dimension components may present more susceptible to uneven chamber cooling or lower tolerance for printer dimensional deviation, and thus increased print failures.

3. Step 3: Print and test

3.1. Introduction

The upcoming section conducts the printing and testing of several selected components. For that, the following areas of research are defined based on the 3DP4R Guide: Test step. (Bolaños et al., 2022). The conducted printing protocol can be observed in Appendix F.

3.2. Quality testing

The initial tests evaluate the individual printed components as they are before assembly. The objective is to determine the overall quality of printed components in comparison to standard IM components and determine whether these qualities render the parts unsuitable for use in the vacuum.

3.2.1. SLS surface finish & roughness

SLS surface finish is rough and grainy, with a roughness ranging from 12.431 to 23.847 Ra, depending on printing conditions and materials (Petzold et al., 2019). In contrast, IM components can exhibit a range of surface finishes, including glossy (0.012-0.10 Ra), semi-glossy (0.05-0.32 Ra) or rough textured (0.8 -18 Ra) (3D Hubs, SPI surface finish), which concluded with regular SLS presenting greater roughness than IM parts.

This difference in surface roughness can impact the responsiveness of moving assemblies due to increased friction, potential particle entangles or adhesion to inner surfaces, leading to particle accumulation and therefore reduced airflow. Thus, achieving a smoother surface through post-processing may be necessary for SLS parts.

Regarding improved surface smoothness, it is recommended to orient that face towards the bottom of the build chamber, while to achieve sharp edges, is best to orient the features towards the top of the SLS building volume (SINTERIT, SLS model orientation).

3.2.2. Accurate printing & details

The resulting prints present high accuracy by achieving to replicate small details (motor grill text) and features (integrated brush details) with high resolution. However, some cases of failed detail are identified.

The text on the motor exhaust grill remains mostly legible (3.30 mm in height), except for the last text line, measuring 1.40 mm in height. Design guidelines recommend a minimum of 4.5 mm of height with a depth of 0.3 mm (Formlabs, Fuse 1 SLS)

The bucket release button icon is faded. For these scenarios, it is recommended a depth of 0.15 to 1 mm (Formlabs, 2021; Xometry, 2020). Notably, the original feature possesses a depth of 0.20 mm (Original CAD measure) but yields unsatisfactory results, therefore, it might be advisable to consider 0.40 mm of depth.

Figure 19: Examples of achieved details. (Top) Motor exhaust grill with proposed embedded text. (Bottom) GF 12 integrated brush with orignal pattern.

Dimensional accuracy

SLS technologies offer ± 0.3 mm tolerances (3D Hubs, SLS design). To assure the accuracy of the conducted printing, a dimensional deviation evaluation is conducted. Appendix G presents the registered results. Measures are taken from identified essential features with a calliper and compared to the CAD files.

The obtained average difference across registered measurements is 0.11 mm, which is consistent with the
It must be acknowledged that the assessment utilized a calliper and manual measurement, therefore the results are subjectable to human error.

findings of Buijserd (2022), who also observed a maximum variation of 0.1 mm across the printed SLS components.

Some cases present clear deviations. The front wheel bearings GF 12 SAMPLE 3 presents 0.45 mm (GF 12, Measure 1) and 0.36 mm (GF 12, Measure 2). Closer inspection reveals the presence of excess material, implying a sandblasting failure.

Table 9: Overview of registered measures from front wheel bearings.

FRONT WHEEL BEARINGS										
MEASURE NUMBER	1		2		3		4		5	
REFERENCE CAD (MM)	3.00		3.00		2.40		7.20		5.40	
PRINTED (MM)	GF 12	PA 12	GF 12	PA 12	GF 12	PA 12	GF 12	PA 12	GF 12	PA 12
SAMPLE 1	2.67	3.08	2.38	2.90	2.38	2.13	6.90	7.04	5.31	5.38
SAMPLE 2	2.80	2.96	2.94	2.89	2.22	2.38	7.27	7.13	5.25	5.40
SAMPLE 3	3.45	3.02	3.36	2.80	2.41	2.24	7.52	6.92	5.53	5.31
MEAN OF DIFFERENCE	0.03	0.02	0.11	0.14	0.06	0.15	0.03	0.17	0.04	0.04
MEAN OF REAL VALUES	2.97	3.02	2.89	2.86	2.34	2.25	7.23	7.03	5.36	5.36

3.2.3. Identified printing failures.

Figure 26 illustrates the several notable print failures. Regarding specific SLS printing failure rates, no universal values are identified in the literature, and the printed components where not addressed in depth in this regard.

Excess of material

Another case is the experienced excess of material in the GF 12 printed components. Examples of this are the rear wheel bearings and screw holes in the nozzle rotation assembly. This may result from a sandblasting error rather than a failed printing failure. The excess of material hinders components' fit requirements, which leads to failed printing results. The occurrence of such failures in components in-house manufactured suggests the potential human error and inadequate post-processing inspection.

Flat surface warping

One instance of a print failure is the warping of the drive head's flat disc. Warping primarily results from part geometry rather than an inherent printing failure. To avoid warping, recommendations include the design of components with flat surfaces, including ribs or support where possible an orienting part at an angle during printing, while preventing their positioning close to the building chamber walls can also reduce chances of warped surfaces (Formlabs, Warping).

Material failure

Finally, some components, like the vortex finder example, present poor finish on vertical surfaces. In cases where the recycled powder is not correctly mixed or presents larger gain sizes, it can lead to a variation in melting temperatures, leading to uneven sintering, and poor surface finish (Formlabs, n.d.)

Figure 26 20:Overview of the identified print failures (Top) Resulting cleaning of excess of material in rear wheels cavities. (Middle) Drivehead flat surface warped. (Bottom) Vortex finder presenting poor finish on vertical surface due to bad mix of new and recycle.

3.3. Assembly testing

A basic assembly level test is conducted by conducting the simulation of a vacuuming scenario at the company Home Lab, focusing on general component performance and observing printed parts behaviour. Components are assembled in a working SPM and results are presented in sub-sections for various observed scenarios.

3.3.1. Fit requirements

The conducted assembly of components reveals that in general SLS printed components do achieve the original fit requirements (see Figure 27). However, components evaluated with a HIGH fit requirement (Press fit) do not achieve the fit solution. For example, the integrated brush exhibits a looser fit than its original counterpart, owing to the identified dimensional deviation previously discussed. Similarly, the tube inlet and end, which employ screws and a press fit solution present play in the assembly due to increased gap with tube connection, even when the original fit seals are employed.

The unachieved press fit solution is of concern for the product functionality as it may result in air leaks, leading to diminishing the suction power, an increase in assembly play, leading to increased mechanical fatigue and lower product quality perception by users. Solutions recommended from manufacturers is to consider the building orientation of parts.

Regarding screw fastening, SLS-printed components are suitable for such a fit solution. Screws are held in place and assemblies do not present major gaps and play. Examples of these cases are the tube end and nozzle rotation assembly (Figure 28). However, during the reassembly of the component, the nozzle rotation assembly screw holes where damaged when excess force was applied.

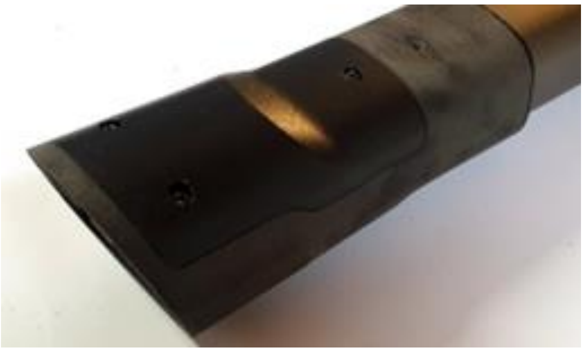


Figure 27: Comparison between original and printed brush (Top). Tube end where the original covers and screws fit as required (Middle). Evaluation of button fit in nozzle end, leading to a successful result.

Figure 28: Screw solutions do present secured fit.

3.3.2. Responsiveness of moving assemblies

As noted earlier regarding the surface finish of the SLS, its rough and grainy surface had adverse effects on the performance of moving assemblies. Notably, the wheel's bearings, nozzle rotational assembly, and bucket release button are significantly impacted.

The bucket release hook and button (see Figure 30) present increased rigidity due to the friction between both components leading to constant jamming when actuated. Nevertheless, the assembly managed to release and hold the bucket, even when attempting to forcefully remove it without pressing the release.

The Nozzle rotations assembly connects the tube to the nozzle, allowing the nozzle to lean from right to left to enhance manoeuvrability. The printed components exhibited increased friction, leading to decreased rotation, challenging the handling experience.

Wheels encountered reduced rotation freedom, primarily due to of the axle's friction with the inner bearings surface, impeding the smooth movement of the nozzle.

Figure 29: (Left)Printed Nozzle rotation assembly tested with the printed wheel bearings (Right) during simulated vacuuming of company Home Labs.

Figure 30: Printed bucket release assembly. Despite its reduced responsiveness it allows for the detachment and lock of the bucket.

3.3.3. Drivehead

The drivehead component transfers the motor rotation to the nozzle, thus identified as relevant for repair. Due to its expected stress during motor-transmitted rotational movement, the component achieved a Med printability score.

Its criticality led to the conducted brush stoppage protocol, where stress conditions are simulated by attaching a cord to a static object (Sofa leg in this case). When vacuuming, the cord entangles and causes the brush to suddenly stop. It is expected that the drivehead can survive these cases.

The resulting evaluation of GF 12 and PA 12 printed drivehead in a cycle of five stoppages reveals no observable damage nor abrasive damage leading to a successful performance.

Specialised equipment for fatigue and continuous cycle testing was not available, therefore the longevity of the part could not be assessed.

Figure 31: Brush stoppage test, where a cord entanglement causes the bush to stop, thus exerting sudden stress to drivehead.

3.3.4. Observed damaged during general testing.

The assembly testing under basic vacuum conditions exposed damage in both GF 12 and PA 12 printed components.

The printed tube unlock button failed when pulled against the couch leg. This highlights a significant concern regarding its suitability as AM spare parts and the strength of SLS when replicating IM components. The tube unlock button is crucial for maintaining a secure lock between the nozzle-tube and tube-chassis, which makes its failure a reliability issue for the product functionality. Further is explored in section 4.

Other cases such as the tube end and main body inlet present bend (PA 12) or brittle (GF 12) failures in their cable routing features.

These cases underscore the mechanical vulnerabilities of SLS components with thin-walled, small features, highlighting the need for component redesign to either reduce part complexity or to enhance essential elements as seen in the tube button.

Figure 32: Examples of observed part damage after assembly testing. (Top) The printed components rear hook failed under light load (Bottom) Tube ends present broken thin-walled cable routing feature.

3.4. Corrective course of action

3.4.1. Vapour smoothing

A brief exploration into the implication of vapour smoothing to enhance part surface smoothness, which has been defined in the surface finish evaluation and the experienced reduced responsiveness of moving assemblies. This method is chosen as it provides smoother surfaces compared to other post-processing techniques (Formlabs, Guide to SLS post processes).

This process reduces the initial surface roughness of SLS from ± 12.43 Ra to ±1.62 Ra, on par with IM dull finish (Engineering product design, SPI; Protolabs, vapour smoothing)

Moving assemblies

Vapour smoothing was applied to the bucket release button and the front wheel bearings. The result does not present an improvement in the assembly's responsiveness. It is observed that the post-process method failed to fully cover the components' surfaces, leaving untreated SLS surfaces in their inner cavities. This partial coverage may explain the observed lack of responsiveness improvement. Notably, the bucket release assembly displayed significant surface damage after use, suggesting potential limitations of the process for sustained abrasion conditions (See Figure 33). Unfortunately, due to time constraints, the nozzle rotation assembly could not be acquired for testing.

The coverage limitation highlights the necessity for a more in-depth understanding of the chemical application process, which might lead to the development of specific protocols tailored to different components. Notably, this observation underscores the challenges posed by complex cavities and geometries for post-processing operations, highlighted in the printability assessment.

Enhanced surface finish

Vapour smoother components do present an enhanced surface finish, reminiscent of that of the IM printed components. The vortex finder's direct implication in the airflow and suction power of the products offers an opportunity to understand potential enhancement in performance if subjected to vapour smoothing. Further evaluated in section 4).

Notably, the abrasive nature of the process erodes the Vortex finder's hook-fit, leading to a less secure fit inside the dust bucket, posing a risk of potential loss during cleaning. To mitigate feature distortion, it is recommended to maintain a minimum of 1mm of thickness (Xometry, Vapour Smoothing).

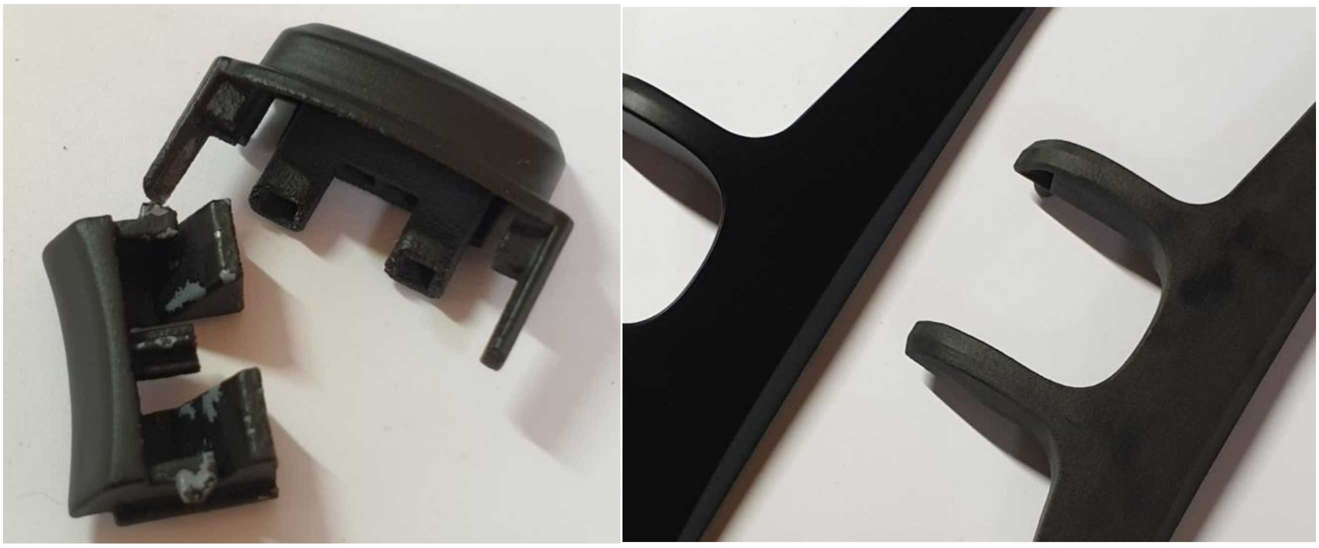


Figure 33: Resulting surface damage of vapour smoothed Bucket release button. It can be seen how the inner cavities of the top element still present the rough SLS surface.

3.5. Conclusion

3.5.1. Quality testing

Surface Finish & Roughness

SLS components exhibited a rough and grainy surface finish, with roughness levels ranging from 12.431 to 23.847 Ra. Notably, this roughness exceeded that of the IM of components, which mostly presented a range from 0.1-3 Ra from the observed surface finish. This surface finish presents implications for reduced responsiveness of moving assemblies (as validated in Assembly testing) and concerns for particle entanglement during vacuuming.

Accurate Printing & Details

SLS printing overall achieved high accuracy in replicating small details and features, while certain components faced challenges. For instance, the text on the motor exhaust grill displayed poor legibility for letters with a height of 1.4 mm, falling short of Formlabs' recommended 4.5 mm text height.

Dimensional accuracy assessment revealed 0.11 mm deviation from reference which is consistent with previous research conducted by Buijserd (2022) and expected SLS ± 0.3 mm tolerances.

Identified Printing Failures

Notable print failures included excess material, flat surface warping, and material failure. Excess material, especially in complex cavities and thin holes, affected component fit requirements, as in the case of wheel bearings. Warping, as seen with the drivehead, primarily resulted from flat geometry features, suggesting the need for design reinforcement with ribs and optimal part orientation during the printing process. Material failure refers to the potential impact of low refresh rate or bad powder mixing, where bigger material particles interfere with the sintering process of layers, leading to poor surface finish.

3.5.2. Assembly testing

Fit requirements

In general, printed components met the original fit requirements, yet press-fit requirements were not met.

For instance, the tube inlet and end exhibited play and gaps, even when original seals intended for increased gap sealing were used. Such limitations could potentially impact product functionality, especially regarding air leaks.

Screw fastening presented to be a viable option, where cases such as the nozzle rotation assembly and the tube end covers are secured.

Responsiveness of moving assemblies

SLS rough surface influenced moving assemblies' responsiveness, including wheel bearings, nozzle rotation assembly and bucket release button. This presents severe implications for product functionality and operability the components are identified as of functional relevance. However, they still maintained a degree of functionality, which can be enhanced by implementing post-processing methods.

Drivehead testing

Among the critical components for the product functionality, the drivehead is identified for the nozzle. The conducted company protocol testing to evaluate entanglement stoppages presented that the component did survive the conducted test, however, due to limitations in specialised equipment, the implications in long-term fatigue could not be assessed,

Observed damages during general testing.

Conducted assembly testing revealed the weaknesses of specific part features such as snap fits, presenting bending (PA 12) or brittle failure (GF 12) and surface scratches (drivehead). These pose a challenge for component eligibility, as thin-walled components might preset high failure rates.

Corrective Course of Action

Given the limitation imposed by SLS surface finish, vapour smoothing was applied to assess potential improvement in moving assemblies and general art surface finish.

While the processed components achieved a similar surface finish to IM-manufactured components, this method presented limitations in improving the responsiveness of moving assemblies. The lack of coverage in component inner cavities, where raw SLS surface remains, might explain the lack of observed improvements. This underscored the need for a better understanding of the process and its influence on part features, as seen in the Vortex finder, whose snap-fit features were eroded.

In summary, the quality testing section highlights the main challenges of SLS printed parts, being the surface finish, press-fit requirements, and the limitations of possible post-processes with recommended courses of actions.

4. Functionality evaluation

4.1. Air flow test

Table 10 reveals recorded airflow and suction power data gathered from the conducted test in the 50 mm plate scenario, representing the maximum airflow capacity of the product. The results present negligible differences between the original and printed components. The quality specialist at Versuni defines that a diminution in airflow of less than 0.5 L/s compared to the original sample does not reflect any perceptible functionality implication. The FDM is the less-performing AM sample, registering a reduction of 0.2 L/s in maximum airflow and, therefore, is within company-accepted margins.

Vapour-smoothed PA 12 does not present substantial improvement over PA 12 and GF 12 samples. This result implies that the geometry has a greater impact in the performance than surface finish. Therefore, higher precision in replicating the original geometry becomes more relevant.

Table 10: Collected air data.

SAMPLE	AIRFLOW (L/s)	SUCTION POWER (W)
ORIGINAL	17.5	2.3
FDM	17.3	2.3
PA 12	17.4	2.3
PA 12 VAPOUR SMOOTH (VP)	17.4	2.3
GF 12	17.4	2.3

4.1.1. Qualitative vacuuming test

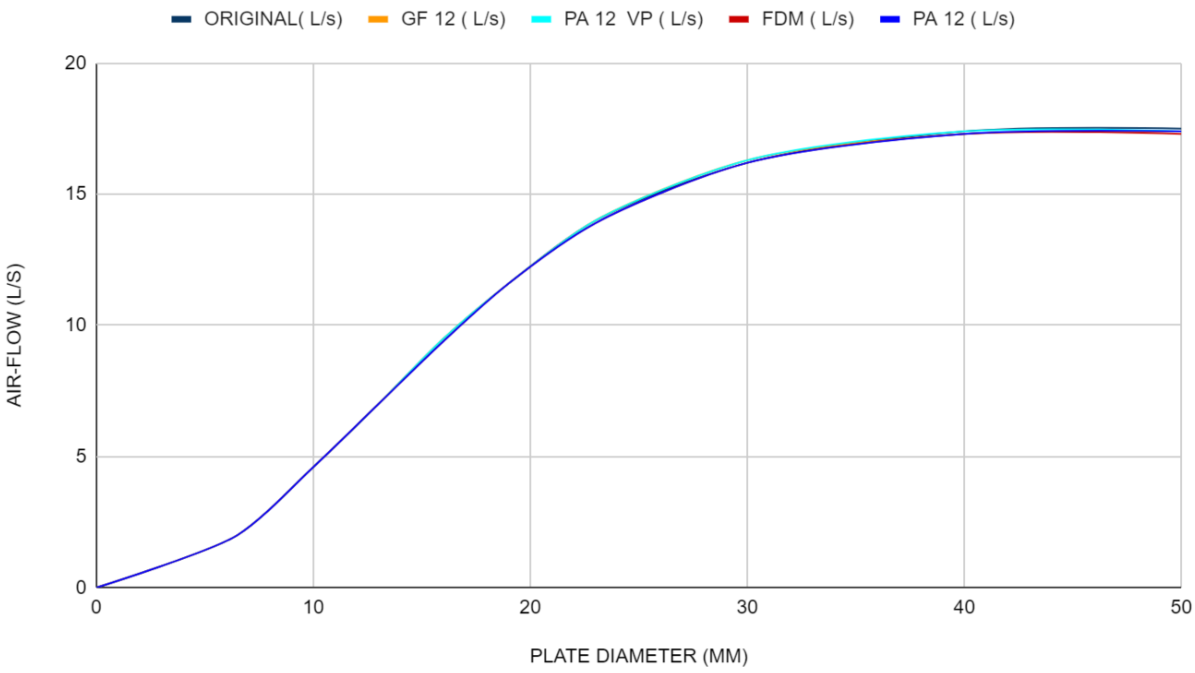
Figure 36 results from conducted vacuuming test. Every printed component performed comparably to the original vortex finder, consistent with airflow test outcomes.

The assessment of heavy particle suctioning already provides insight into the performance of the pat. As expected from the original component, every printed sample was achieved to redirect the particles into the second chamber.

In cases involving synthetic hair, samples faced difficulties, leading to chamber obstruction. This result indicates that the phenomenon is not unique to the printed component, as the original one presents exact same performance.

It was also noted that the original vortex finder, composed of two IM-manufactured parts, encountered hair entanglement in its crevice in each cycle of the test. Conversely, AM-printed unibody components did not exhibit similar phenomena. This observation implies that AM capacity for unibody printing may offer the opportunity to present less maintenance.

Figure 34: Original vortex finder sample presented particles entangle in its two-part joint section.



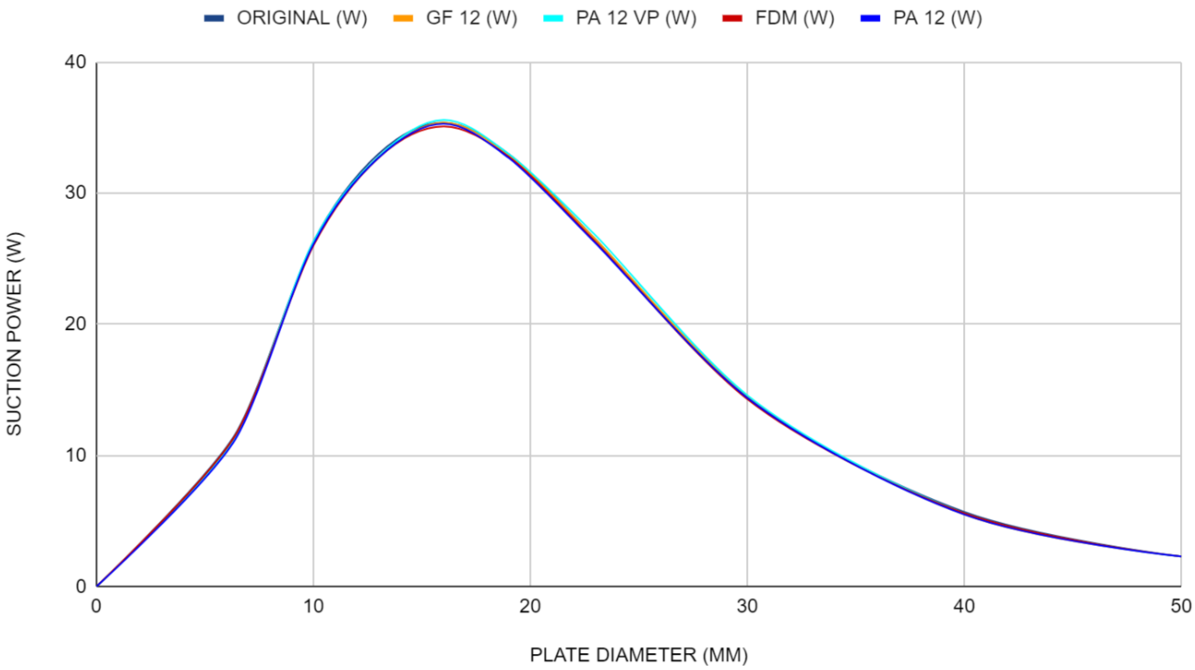


Figure 35: Obtained results between airflow (L/s) (Top) and suction power (W) (Bottom). The graph presents how closely each printed version performs to the original components. Presenting the vortex finder as one of the major opportunities of AM implemented spare parts on the case study.

ORIGINAL COMPONENT	FDM	PA 12	PA 12 REDESIGNED
			

ORIGINAL COMPONENT	FDM	PA 12	PA 12 REDESIGNED
			

Figure 36: (Top) Vacuum conducted with heavy particles (lentils), where every component presents same result as the original. (Bottom) Experienced obstruction when vacuuming hair particles.

4.2. Strength requirements

The use of the vacuum puts certain components under high mechanical stress. Such components are also prone to breakage, hence their high priority for repair as indicated by the model. However, effective repair necessitates spare parts that are robust enough to withstand the stresses of regular use and mishandling.

4.2.1. Wheel bearings

Wheel bearings represent a prime candidate for this test. Wheel bearings are expected to endure substantial forces attributed to their role in supporting the product weight and the force exerted by users during vacuuming activities. This is demonstrated by the high number of replacement wheel bearing replacements the company provides (the real number is confidential). In addition, the nozzle is expected to experience potential drop impacts due to users mishandling and the way the product is stored, holed upright against a wall. The significance of wheel bearings as repair priority is due to their lack of availability as standalone spare parts and their relevance for the nozzle's correct functioning.

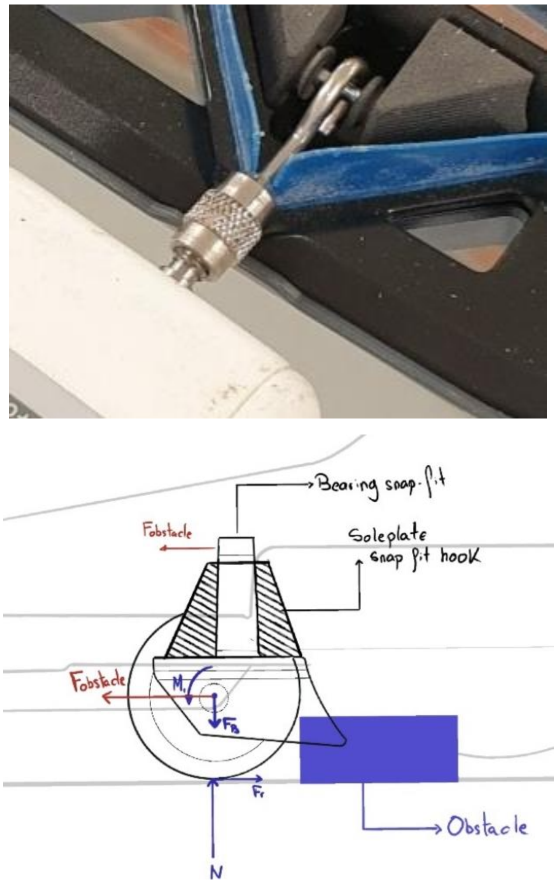


Figure 37: (Top) wheel bearing strain test setup, measuring the required force with a digital force gauge. (Bottom) Illustrative scenario from company protocols of bearings impacting against immovable object.

Strain test

The strain test simulates scenarios where wheel bearings are pushed/pulled against immovable features (e.g., protruding nails, tiles, pavement) (see Figure 37). For that, a digital force gauge is used to measure the peak force registered before failure, either by brittle failure or by snapping out of position.

Figure 38 presents the registered peak forces before failure for both cases, where it can be seen the PA 12 falling in between GF 12 and the original performance. Additionally, Figure 39 shows the closer behaviour of PA 12 to IM components due to its ductility, surpassing the elastic modulus of both components leading to an instead of the brittle failure as experienced by the GF 12.

The rear housing PA 12 and original components present similar results, where the screw hole and the side snap fit present a brittle failure. In the case of GF 12, the structure was not strong enough, leading to complete structural failure.

In the case of the rear housing, every tested component suffered a brittle fracture. The GF 12 presented the most pronounced material failure, where the housing snapped in two segments. Whereas the PA 12 and the original components presented failures localised in the observed target features, the screw hole and side snap fit.

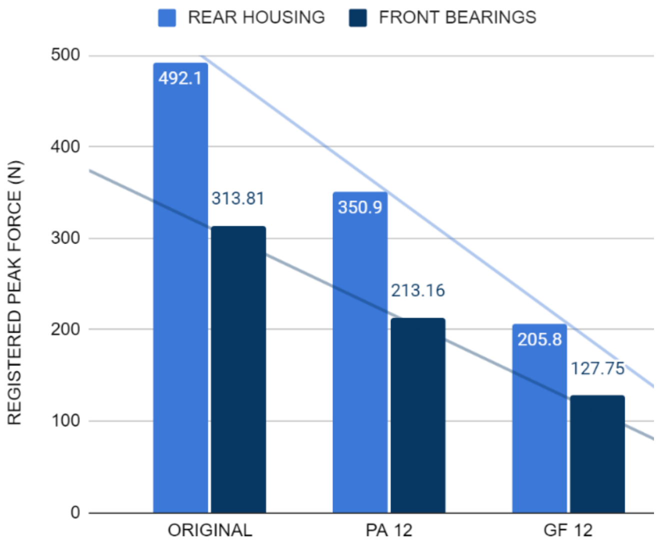


Figure 38: Registered peak forces before fail.

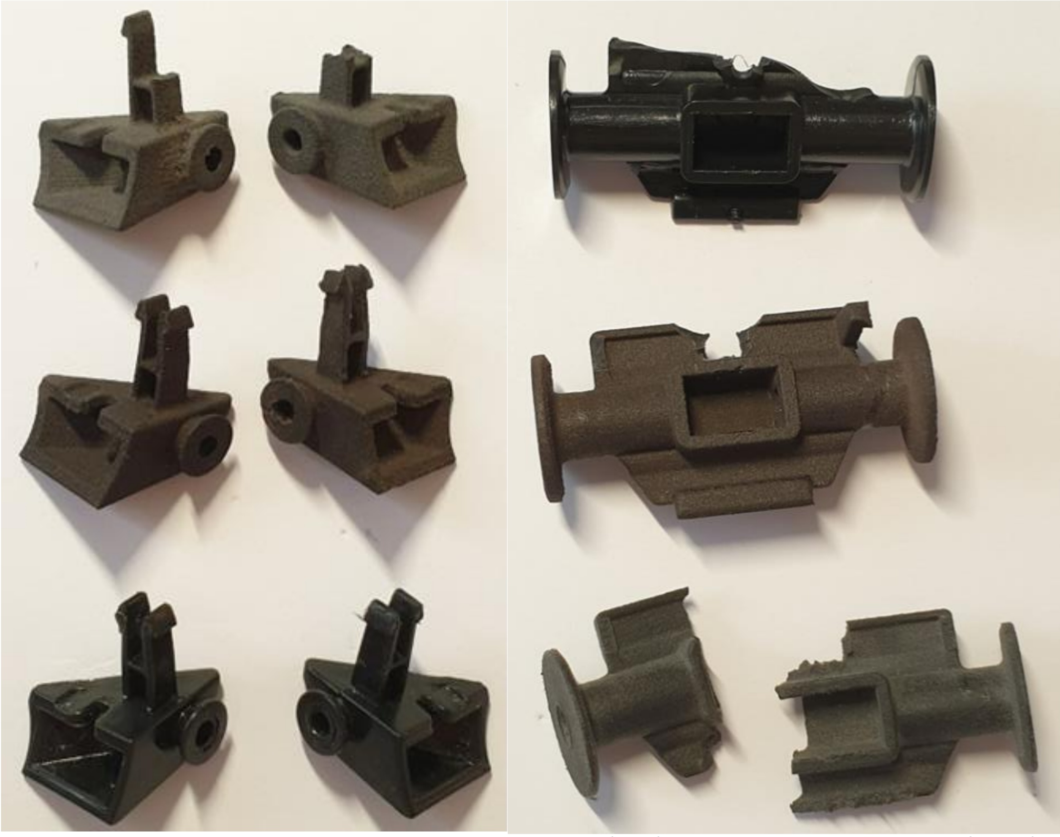


Figure 39: Outcomes form the conducted test. (Left) front wheel bearings, (Right) rear wheel housing. The GF 12 front bearing's exhibit a failure where two thin-walled cantilevered pillars are located, above a thicker-walled hollow structure. The rear housing PA 12 and original components present similar results, where the screw hole and the side snap fits present a brittle failure. In the case of GF 12, the structure was not strong enough, leading to complete structural failure.

Drop test results.

The nozzle is also expected to experience significant stress from dropping as defined by company protocols, with the wheel bearings absorbing the impact. To simulate this, the nozzle assembly is dropped from different heights to evaluate the effects on the wheel bearings. Starting from 30 cm up to 200 cm with the addition of 10 cm each cycle (see Figure 40). While the original and PA 12 printed versions did not present notable damage, the GF 12 component presented damaged housing and snap fits. This test illustrates the advantage of PA 12 for impact resistance against GF 12, as presented by the material manufacturer (Formlabs, n.d.)

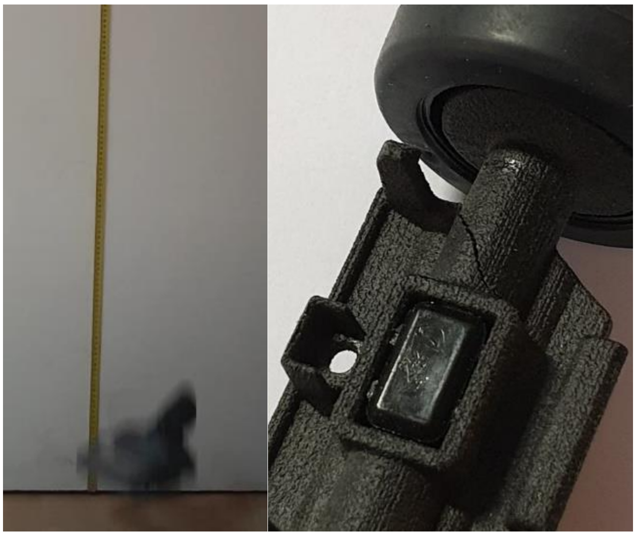


Figure 40: (Left) Drop testing setup, featuring the use of a measuring tape for height registration. (Right), image of the GF 12 rear wheel housing displaying a fissure after the test.

4.3. Tube button

The previously conducted Assembly evaluation (section 3.3) revealed the weakness of the tube button, which poses high functional relevance by assuring the secure lock between bodies. The rear hook, intended to lock the inlet feature in place failed under light load, therefore, it offers the opportunity to evaluate the implications of redesigning a component for current assemblies.

4.3.1. Corrective action

A redesign is proposed to evaluate the difference in performance from regular GF 12 and IM components. The redesign consists in the reinforcement of essential features, as seen in Figure 42 with no specific wall thickness.

Test setup

The test conducts a strain test, simulating the experienced scenario of pull force causing the tube button failure. To evaluate the effectiveness of the redesigned geometry, a new set of tube connections was 3D printed. The original tube connections were found to be unsuitable due to the tube button not fitting correctly.

4,3,2 Results

Table 11 present the identified failure point in the assembly. Contrary to assumed, side fits did not fail. However, GF 12 rear hook presents brittle failure, while original button is deformed.

This case serves as a clear illustration that directly replicating and printing 1-to-1 the original geometry, while achievable, is not recommended. This is primarily because AM-printed components tend to have lower density and structural strength compared to IM parts. This difference is due to the layer-based nature of the AM processes contrary to the one layer of IM (SINTERINT, SLS printing).

This scenario brings an interesting implication, the ratio among material volume and part strength and its implication in increased weight, material suage and cost.

Unexpectedly the test also revealed the limitations of the printed tube inlet extrusion for hooking with the tube button which presents obvious signs of damage, being the cause of the abnormal load registered after initial cycles, leading to a register of only 5.79 N percentage of the GF 12 redesigned initial value.

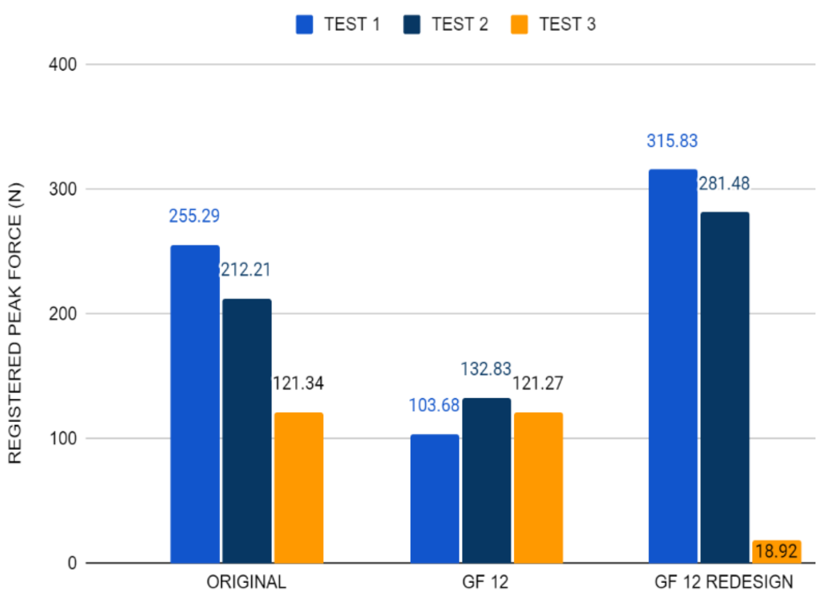


Figure 41:(Left) Obtained results from conducted strain test (Right) Strain setup with designed tube inlet-end connection.

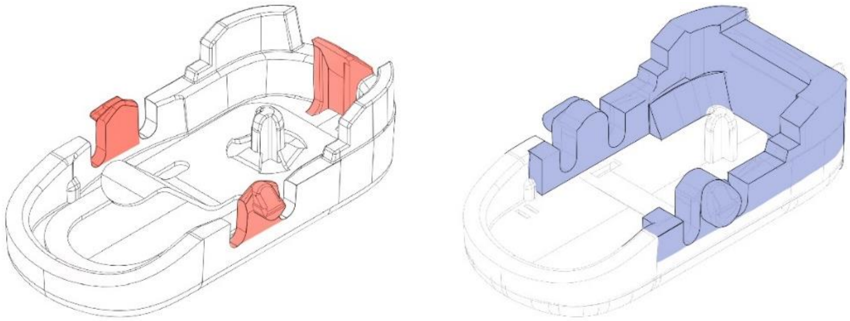
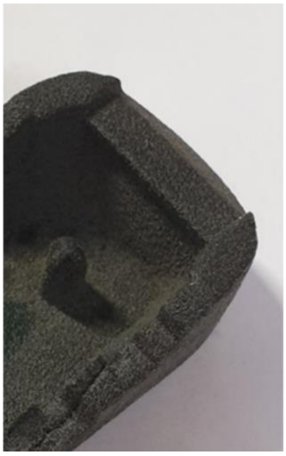


Figure 42: (Left) Original printed geometry identified vulnerable features. (Right) Conducted reinforcement of geometry over assumed parts strength requirement.

Table 11: Overview of part behaviour after strain test.

Original feature	*GF 12*	*GF 12 redesign*	*Printed Tube inlet*
			
The original components feature is deformed and bent, leading to a lack of attaching with inlet extrusion.	GF 12 feature presents a fragile and brittle failure at the line of wall height.	It was not possible to assess failure points due to printed assembly failure in the redesigned GF 12. However, still registered higher forces while not presenting damage to the surface.	The printed Inlet hook feature presents damage, causing the tube buttons hook feature to slide out.

4.4. Flexible components

4.4.1. TPU flexible components: wheel tire

The wheel tire is evaluated as of HIGH functional priority. The original component is manufactured in TPU, which is available for the selected SLS technology. To further understand the implication of alternative flexible SLS materials, an additional sample is printed in TPE.

The conducted evaluation presents that TPU material is preferable due to its stiffness and abrasion resistance over TPE (Xometry,2022). However, while the abrasion test reveals barely noticeable tire track marks compared to TPE (see Figure 44) the printed TPU tire smooth finish presents a reduced grip compared to the original components. This may lead the Nozzle to slip, hampering its manoeuvrability.

Figure 43: Overview of wheel assembly. Where a core (Left) and the tire (Right) company the multi-material wheel (middle)

A multi-material component

The wheel necessitates a redesigned multi-component part, with an ABS core surrounded by the TPU tire. Despite the effective printing of the separate elements, their current geometry is designed for the overmoulding manufacturing process (Formlabs, Overmoulding and Insert Moulding), and does not allow an assembly solution. This results in a failed assembly given the existing geometry and despite the results from the framework (Med printing scores for both core and tire).

Figure 44: TPE printed wheel rubber (middle) leaves a dark stain when rubbed against a piece of paper, while TPU printed rubber (Right) presents no stain.

4.4.2. High flexibility: motor suspension and bucket inlet seal

Both the original motor suspension and the bucket inlet seal (see Figure 45) are characterised by their elasticity.

The motor suspension minimizes the vibrations caused by the motor, while the bucket inlet seal prevents air leaks and any particle from exiting the bucket-body connection, potentially entering the motor air inlet.

Therefore, their greater flexibility is required for shock absorption, vibrations, and to reduce gaps in between components, for that, TPE SLS material is selected, being the only more flexible than TPU.

Stiffer than the original components

The printed TPE motor suspension and bucket seal present to be much stiffer than the original Styrene-butadiene Rubber (SBR) components. SLS TPE material is indicated to have a hardness of 90 Shore A by the manufacturer (SINTERINT, TPE). While the exact shore of the SBR components was not possible to measure, similar gasket material can present 35-70 Shore A (MatWeb, SBR; GeekTech, SBR rubber gasket), making it much softer than the printed component and therefore more suitable for shock absorption.

The implications of the stiffer TPE components were further verified by an assembly test, which revealed that the printed component does not deform enough to allow for the vacuum to be assembled.

The resulting print represents a failed solution, despite the eligibility evaluation score of High (bucket lid seal) and Med (motor suspension)

Figure 45: The TPE powder, despite being more flexible that TPU does not accomplish the flexibility requirement of the original motor suspension (Left) and bucket inlet seal (Right).

4.5. Conclusion

The conducted evaluation of specific attributes further insights into the limitations and considerations for SLS printing of spare parts components:

Airflow performance

The airflow test conducted to evaluate the performance of the original vortex finder, FDM, PA 12, GF 12 and PA 12 vapour smoothed samples, present negligible differences. Interestingly, neither the vapour smoothed sample nor the FDM sample presented notable differences, discarding the initial assumption of surface finish influence on product air performance.

These results are supported by the conducted qualitative vacuuming test, where every printed sample performance mirrored that of the original component.

Strength requirements

The results present that GF 12 and PA 12 registered an average of 44.85 % and 69.61 % respectively of original IM components peak forces.

However, these results do not account for the observed permanent deformation in PA 12 samples as seen in the wheel bearings. Therefore, while PA 12 registers higher peak forces, that does not translate to enhanced part and functional integrity.

PA 12 does behave similarly to IM materials (ABS, POM), offering a degree of impact resistance as seen in the drop test. GF 12 on the other hand presents to be more brittle with major stiffness, this can be more effective for scenarios where components are expected to be less subjective to flexure such as the tube unlock button.

Part redesign & Domino effect

The conducted redesign of the tube button presents a clear advantage over the original geometry printed parts. The redesigned tube button registers a 137 % increase in strain peak force.

This presents an additional dilemma, the increased volume of material per increased strength ratio and implications such as increased weight and material cost.

Redesign of tube button and wheel bearings testing insights unveiled a critical limitation for AM spare parts in current products: redesigning one part may necessitate concurrent redesign of other assembly components for fit compatibility.

Flexible components

In the evaluation of flexible component printing from SLS technology, the original TPU wheel tire was compared to SLS TPU and TPE materials, with TPU being preferred for its stiffness and abrasion resistance. However, the printed TPU tire exhibited reduced surface grip due to its smooth surface. Additionally, the wheel, being part of a multi-material part, presented a challenge. While individually the tire (TPU) and the wheel core were viable to be printed, their current geometry design based on the overmoulding process does not allow for an assembly.

The TPE printed samples for the motor suspension and bucket inlet seals also presented a challenge as the original SBR material offered greater flexibility than the SLS printed outcome. This influenced the fit requirement of the printed components, due to their inability to be compressed as required.

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Part 5. Discussion

1. Findings -General overwatch chart

This section complies with the primary findings from the conducted validation process, structured to facilitate corrective actions and guide future research directions. The results are categorized into two main assessment areas: Printing of components and Eligibility Evaluation insights.

Table 12: Overview of main findings.

	Finding/result	Cause	Corrective action
	Printing of components		
1	Printed soft components are not soft enough.	While TPU may present an opportunity for wheel tire printing, the TPE materials present to be stiffer than required, leading to not fitting in the assembly and sealing challenges. Identified SBR components present a range of 30-70 Shore A, while TPE offers Shore 90 Shore A.	1.Explore alternative printing technologies (Xometry, 2023): -SLA Ture silicone (50 Shore A). -Carbon DLS SIL 30 (35 Shore A) 2.Revise the current seal design for lesser structural integrity by reducing wall thickness and ribs.
2	Press-fit requirements not achieved.	The conducted printing and assembly of components showed that the high fit requirements of components were not achieved. This presents serious implications for products such as vacuum cleaners and their required airtight assemblies.	1.Develop of personalized seal for AM printed components. 2.Enhance male meting features dimensions up to 0.10 additional, as this is the observed average dimensional deviation.
3	Multi-material components necessitate additional design considerations to achieve effective printing solutions.	A brief exploration of the presented multi-materials (wheels) reveals the failed print solution due to their current geometry design for the overmoulding manufacturing process. These components would require an alternative design solution, rendering the current print as a failed result.	In the case of the wheels, a unibody TPU design can be adopted as proposed by Buijserd (2022).
4	Vapour smoothing enhances surface finish but can introduce the risk of feature erosion while no improvement is noted in moving assemblies.	1. The process's abrasive nature can also erode part features, especially if thin-walled and small, affecting part fit requirement as observed with vortex finder 2.The lack of responsiveness improvement in moving assemblies could be due to incomplete coverage of parts' inner cavities attributed to part orientation during chemical exposure.	1.To prevent significant feature erosion, it is recommended to maintain a minimum of 1mm of thickness for original geometries. 2.The potential abrasion resistance limitation prompts exploration of alternatives such as ceramic coating, coating, said to provide enhanced wear resistance (Formlabs, Guide to SLS post processes; Cerakote, Cerakote H-140 Bright White)
5	Airflow test reveals optimistic result for SLS	The conducted Airflow test reveals optimistic results for the SLS printed Vortex finder, additionally, it also reveals	1.Conduct a deeper understanding of Vortex's mechanical strength, especially on its thin-walled side fit.

	printed Vortex finer spare parts.	the opportunity of using more cost-effective technologies such as FDM, as they perform similarly while the clear result is that vapour smoothed par did not perform significantly better.	2.If vapour is smoothed, follow recommended geometry considerations to prevent loose fit.
6	Redesign operations for current product constrained by existing assemblies' relationship and available space.	The extent to which a component can be redesigned to improve its mechanical properties is limited by other components' direct relationship. For instance, the tube button's redesign necessitated the redesign of the tube end-inlet assembly, resulting in additional time demand.	1.Identify components' relationship depth to other components to assess the complexity of the task 2.For future products, design repair priority components with AM in mind, even if they are initially manufactured in IM. This approach ensures that parts have longer lifespans due to built-in reinforcement measures. In the event of a failure, AM can support directly without requiring component redesign.
7	SLS surface finish challenges moving assemblies' responsiveness.	The Assembly evaluation conducted unveils the impact of the surface finish resulting from the SLS (Selective Laser Sintering) process on the functionality of moving assemblies, specifically the wheels and nozzle rotation assembly. This surface finish detrimentally affects their responsiveness, leading to performance issues.	While the used vapour smoothness did not offer a clear improvement, more post-processing testing is required as the limited sample could not effectively assess the effectiveness.
8	Thin-walled features exhibit a significant reduction in structural integrity.	The redesigned tube unlock button, which includes reinforced features, demonstrated a higher peak force compared to the original components. The modification ensures suitability for the specific scenario and provides long-term durability.	Part reinforcement is crucial as 1 on-1 reproduction of original features will lead to lower strength and integrity of parts. For that, ribs and surface thickness are presented to work effectively in the case of the tube button.
9	Presence of SLS failures lead to a challenging repeatability of printed components and their fit requirements.	Three print failures are identified, excess of material in cavities, warping and material failure. While an excess of material in cavities and material failure can be linked to a process failure the warping is directly influenced by part geometry design	1.Implement a more rigorous post-sanding inspection to prevent untreated features. Additionally, reduces the cavity complexity of components to prevent excess material. 2.Prevent flat surfaces and, if not possible, implement ribs and support structure while orienting part at an angle in the print bed.
	Eligibility evaluation		

1	Data provided by company is not precise enough for effective component eligibility evaluation.	The data provided by the company has a significant limitation as it presents values at the assembly level. This limitation affects the precision of the evaluation and the selection of individual parts, leading to components with apparent less failure frequency registering similar repair rates.	Enhance designer-company specialist interaction to assess and interpret gathered data with experts' knowledge and experience.
2	The printability assessment of components present subjectivity when previous product experience or technical understanding is lacking.	In certain cases where part complexity grade remains unclear and an understanding of necessary strength requirements is lacking, the assessment of component printability can lead to wrong results.	1.When no clear threshold of complexity is viable, use part dimensions and volume as a reference, as the higher size/volume, the higher challenges can bring for printing failures, material usage and build space occupation. 2.Enhance the definition of expected part requirements (fit tolerances, load-bearing capacity, chemical resistance, etc.) in company-provided documents like the BOM list. This will provide evaluators with a clear and comprehensive reference for their assessment.
3	Multi-material components eligibility is not accurate, they present a failed result.	The current framework does not account for multi-materials, instead, it assesses the individual components within, which, as in the case of the wheels, can be printed. However, multi-materials present a distinct join type, which does not allow for the printed elements to be assembly. Thus, leading to a failed solution.	Multi-material components require redesign solutions, making them unsuitable for the current eligibility criteria. Consequently, it is advisable to introduce a new category within the Cut-off criteria to identify and group multi-materials for later review.
5	Advocating for Modularization and Standardization	The identified common components among both products (wheels, buttons, switches, etc.) present the opportunity to serve as a facilitation for a rapid implementation of AM solutions for current and future products.	The eligibility evaluation can include a criterion to identify those components that are shared among other products to receive a positive score.

2. Concept evaluation

2.1. Introduction

This section discusses the framework's iteration based on acquired validation insights, paving the way for future research. Final proposed framework can be found in Reference Appendix.

2.2. Cut-Off Criteria

2.2.1. Multi-material criterion

As proposed in the gathered insights, multi-laterals are currently unfeasible for print unless an alternative design solution is proposed. For this reason, a cluster to identify and categorize multi-materials is proposed.

Thus, one suitable component has been developed, and design solutions for multi-material components can be conducted.

2.3. Decision-making assistance

The framework assessment of part attributes for AM spare parts eligibility (e.g., demand volume, flexibility, press-fit among others) can also be used to provide further insights into the following areas:

- Material and AM recommendations: Based on practical study, SLS presents limitations in various scenarios: cost-effectiveness (FDM vortex finder), transparent printing (SLA) and available flexible materials (Only TPU available from Formlabs). Alternative materials and technologies can be implemented based on component requirements.
- Post-processes suggestions: Based on part requirements and conditions (Abrasion resistance, waterproof, surface finish, colours etc).
- Economic feasibility: Considering demand volume, AM technology, material, and post-processing needs, the cost can be estimated Comparing it to traditional manufacturing cost, can help identify the break-even point.
- Environmental impact: A Life Cycle Analysis (LCA) comparing current IM processes with a digitalised AM scenario can yield a per-part carbon footprint estimation, which, when multiplied by demand, offers an overview of sustainability implications.

2.4. Criteria iteration

To support the newly implemented functions, insight gathered from the validation process and literature research, some of the criteria are revised.

2.4.1. Printability

Material flexibility

To effectively assess the material type required for the part, a new scale is proposed. Note that even the same material type can vary in hardness (e.g., TPU can range from 95 A to 86A, and SBR range from 30-95 A), therefore BOM list should specify exact material qualities (Xometry,2023; Rahco Rubber, n.d)

-Low flexibility: Hard plastics or flexible parts based on hard plastics.

-Med flexibility: Wheel tires (TPU), soleplate and hoses (PVC)

-High flexibility: Seals & motor suspension (SBR), friction interfaces (TPE).

ELEGIBILITY EVALUATION

PART DESCRIPTION	REPLACEMENT AVAILABILITY	PRINTABILITY	PRINTABILITY												SPARE PARTS SUITABILITY
ASSEMBLY			PART FIT REQUIREMENT	COMPLEXITY OF FORM	COMPLEX CAVITIES	DIFFICULTY GEOMETRY	STRENGTH	FLEXIBLE	ABRASION	TRANSPARENT	SMOOTH SURFACE	FINE DETAILS	HIGH TEMP	WATER RESISTANCE	
EXAMPLE			MOVING PART	SIMPLE GEOMETRY	NO	3-MAIN BODY ++FEATURES	HIGH >85 MPA	NO	NO	NO	NO	NO	NO	NO	
EXAMPLE			NORMAL FIT	CURVED	YES	1-SINGLE BODY	MED 30 -85	YES	YES	YES	YES	YES	YES	YES	
EXAMPLE			MOVING PART	SIMPLE GEOMETRY	NO	3-MAIN BODY ++FEATURES	HIGH >85 MPA	NO	NO	NO	NO	NO	NO	NO	
EXAMPLE			NORMAL FIT	CURVED	YES	1-SINGLE BODY	MED 30 -85	YES	YES	YES	YES	YES	YES	YES	

Transparency

In a scenario where additional technologies are considered exact transparency can influence material and technology type:

- Clear: SLA is an effective solution, yet, to achieve complete transparency additional processes are required due to surface irregularities and material impurities, which can affect the transparency grade of parts (All3DP, 2023; Xometry, 2023).
- Translucent: Translucent requirements are best suited for AM due to the inherent translucency in regular SLA or FDM output. If required, additional processes may be required (e.g., sandblasting and coat painting) (Sculpteo, 2019).
- No (Opaque)

Inclusion of initially discarded criteria

Some initial excluded criteria from the 3DP4R Guide (Bolaños et al., 2022) can be relevant for other scenarios and product categories. To make the framework universally applicable, criteria such as heat resistance, chemical resistance, component occupying volume and water resistance should be included.

2.4.2. Priority for repair & spare parts

Modularity and standardization

Understanding the value of modularity and standardization in the opportunity to identify common solutions for multiple components, those parts that are shared among other products (e.g., wheels, buttons, switches) or can be standardized (e.g., vortex finder)

Table 13: Refined Eligibility Evaluation Table based in acquired insights.

SPARE PARTS SUITABILITY							REPAIR PRIORITY	REPAIR PRIORITY					ELIGIBILITY SCORE	PRIORITY	/10	AM FOR PRINTING	/10	AM FOR SPARE PART	/10	ELEGIBILE ?
SHARED COMPONENT?	DEMAND VOLUME UNITS	VOLUME (HML)	PART VALUE (E)	PART VALUE(HML)	MIN SKU UNITS	MIN STOCK LEVEL		STANDALONE SPARE PART	FUNCTIONAL IMPORTANCE	FREQUENCY OF FAILURE	FREQUENCY OF FAILURE (HML)	COST OF REPLACEMENT (HML)								
YES	50	HIGH	50	HIGH	50	HIGH		YES	HIGH	50	HIGH	HIGH	NO	HIGH	9	MED	7	LOW	3	NO
NO	30	MED	30	MED	30	MED		NO	MED	30	MED	MED	YES	MED	5	MED	5	MED	5	YES
YES	20	MED	20	MED	20	MED		NO	MED	20	MED	MED	YES	MED	5	MED	7	MED	5	YES
NO	10	LOW	10	LOW	10	LOW		YES	LOW	10	LOW	LOW	NO	LOW	0	MED	5	MED	7	NO

3. Project conclusion

3.1. Limitations of current work

Access to fatigue and precise measuring equipment

Company protocols present the importance of evaluation part durability and fatigue tests. These considerations could not be assessed due to a lack of access to required equipment. Therefore, the long-term implications of the findings could not be assessed.

The use of a calliper for dimensional deviation inspection introduces the potential for human error in addition to any inherent device imprecision. For that, it is advisable to employ 3D scanning or coordinate measuring machines (CMM).

Spare parts attribute criteria

The available documentation at the company did not allow for further exploration of criteria to support the assessments of components' eligibility for spare parts. From the identified list at, only three criteria could be backed by company-provided documentation, which can present a limited assessment of the component's suitability for spare parts.

Conducted testing and part evaluation.

The conducted testing was limited in scope due to time constraints, which in turn resulted in a more superficial and qualitative examination. Although it offers a basic understanding of SLS and IM components' implications on strength, airflow and fit considerations, further research is required. For that, the criteria defined by the 3DP4R Guide and part-specific use-scenarios can be used to define a specific test protocol to identify parts' limitations and potential redesign solutions.

Design guidelines

As an extension of the limited printing and testing of components, the resulting solutions and guidelines are present in a generic manner. This is because each component requires thorough research and further understanding.

Complete evaluation of acquired results from the Eligibility Evaluation framework.

Due to the limited time and the number of components, the precise assessment of the proposed framework's results could not be conducted. While some of the assessed components do match their assigned printability score, others presented greater limitations, such as the case of the tube button. A correlation between identified legible components, printability scores and criteria could not be fully explored.

3.2. Future work

End-User feedback and behaviour

Implementing AM spare parts for repair can raise users' concerns about the service and repair quality. However, it also holds the potential to elevate repair awareness and value by highlighting the commitment to personal-owned products and sustainability using AM spare parts. Future research in this area can bring the opportunity to change user behaviour from product disposability to product appreciation, crafting personal experiences and stories.

Packaging design

The communication of a sustainable strategy as the enhancement of repair and the commitment to AM should be reflected in the packaging used or the delivery of printed components. Future research can explore the use of sustainable packaging materials as well as consumer behaviour.

Digitalized support & data gathering

The digitalization of AM spare parts manufacturing brings the opportunity to develop a new digital platform (e.g., web page) for users to conduct troubleshooting and pinpoint required replacement components to be AM printed. In this scenario by requesting images and the exact component required, further understanding of component failure motives and exact part demand volume can be acquired, thus acquiring more precise data about repair and demand values.

Personalized accessories & community

AM enables personalized products to each user's needs and desires. From improved accessibility solutions for persons with disabilities to vacuum cleaners and wall mounts designed according to house and room aesthetics. Furthermore, the development of a community where users can share their designs or solutions based on the products from Versuni can strengthen client loyalty and commitment to the company.

LCA and cost-considerations

AM claims on improved sustainability should be further explored. This can be conducted by analysing the current supply chain scenario and envisioning the advantages posed by AM technologies. Similarly, the cost-effectiveness of the technology should be conducted by understanding the break-even cost compared to IM production. This study can further enhance the current eligibility framework by providing an overview of the expected cost and life cycle environmental impacts.

Thresholds value precision

Current scoring is conducted by defining the 0.25 percentile of the total registered values (e.g., demand volume). Which is a simplified solution from the actual capabilities of AM. Conducting a limited run of AM-printed spare parts to evaluate the manufacturing capability of suppliers can bring exact limitations and values for the demand volume, lead times, cost and so on.

AI-driven Printability assessment

The use of AI and camera-vision is widely used for quality control scenarios. The data collected per component could be integrated into an assisted printability program, which can more precisely evaluate the printability of components in accordance with the technology selected.

The conducted research project and framework iteration identified new research opportunities, not only to enhance the framework capabilities but also new research directions pertinent to the overarching vision of AM use for spare parts.

3.3. Key contributions & addressed challenges.

The main objective of this thesis was to identify a strategy to identify and select components suitable to be AM printed. As part of the initial exploration of Versuni in the realm of AM printing for spare parts, one of the key initial concerns was how to determine which components could be effectively AM printed. To address this concern, an eligibility evaluation framework is proposed, which not only measures components' printability but also strategically prioritizes essential components for repair activities, considering OEMs' perspective and supply chain challenges.

The research and proposal build upon existing research from TU Delft in AM replacement printing, particularly in the context of self-repair scenarios. By exploring an alternative perspective from the OEMs', the project contributes to the expanding knowledge of the university's experience in the importance of AM for repair.

Regarding printing and part manufacturing, the conducted practical study brings light to the limitations of the current components design for their effective implementation as AM printed spare parts, requiring redesigning for enhanced mechanical strength. While the study gathers further qualitative results, it establishes a foundation for future research within the company goals.

The resulting framework effectively narrows down the component's selection for AM printing, allowing companies to prioritize key components for repair operations while providing a comprehensive assessment of each component's attributes and challenges (e.g., printability, spare parts attributes). This framework is further iterated following the identified practical study insight with proposed solutions for framework precision. While a further iteration would be needed, the framework presents opportunities not only to improve its accuracy, but also to enhance its functionalities too.

3.4. General recommendations to Versuni

To enhance the framework's effectiveness; it is imperative to revise the objectives of the company and the subsequent scoring of the criteria to reflect that. This necessitates engaging in an open discussion with company experts to better identify eligible components and to define a strategy for the upcoming AM spare parts manufacturing and logistics structure.

To elevate the company's expertise in AM, it is fundamental to enhance the in-house capabilities at the workshop. From a prototyping sole focus to an end-user production capacity. This involves expanding the material options, including advanced post-processing capabilities, and creating a collaborative space where every professional at the company can participate in learning activities. This investment can empower teams to make well-informed decisions when designing future products while assuring that all specialists at the company can grasp the scope of AM opportunities and limitations.

Regarding the vision of future product design, AM should be a fundamental consideration instead of an afterthought. The observation from the conducted research presents the limitations of adapting the current components' design to that of effective AM printed components, as seen in the case of the tube button. By proactively designing future components with AM in mind, this is by designing their geometry to be the best suited for AM printing and durability, not only will the product last longer, due to the reinforced geometries, but in case of experienced failure, AM will support an efficient repair solution, enhancing the sustainability and resilience of the company products.

3.5. Reflection

This project has posed a personal challenge in my pursuit of becoming a sustainable-driven designer. During my internship, I had the opportunity to explore how different circular strategies could impact product design, being repair one of them. This grew my enthusiasm for envisioning how alternative design strategies could develop into more sustainable products and activities.

Regarding project process and outcomes, while the overarching goals and activities aligned with the intended scope, the execution and development of the project lacked well-defined scope, objectives, and goals. This limitation impeded the depth and extent of the result, as well as the effective communication with my university and company mentors.

The underlying issue was my limited experience in executing such specific and technical project. Despite the guidance of experts in the field, I struggled to effectively navigate and adapt to the circumstances, a vital skill for designers.

Nonetheless, the project allowed me to enhance my lack of experience with spreadsheets. For instance, in the initial selection process for eligible components, I created an intricate, confusing, and time-consuming solution. However, through iterations and consideration for the framework users, I achieved a simpler approach by assigning a binary value of 1 (High or Med scores) or 0 (Low scores) and by multiplying the results, only those components that present eligibility score 1.

In conclusion, while the execution was hampered by my lack of adaptability, decision-making and creativity, I believe this project offers my personal grain of sand to the understanding of the value and opportunities of AM for spare parts manufacturing.

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Appendices

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Appendix A

Figure1: User @21JCW_103227 designed SpeedPro Max vortex finder used for quotation (Yeggi webpage, 2022)

Appendix B

4. OVERVIEW OF AM TECHNOLOGIES AND MATERIALS

		COMMON MATERIALS	COST (h)	SPEED (cOMPARING MODELS IN OFFICE)	LEAD TIME (DAYS)	TOLERANCE	TOLERANCE (MM)	BUILDING VOLUME	BUILDING VOLUME MM3	BUILDING VOLUME RECOMMENDED (MM)	LAYER THICKNESS	LAYER THICKNESS (MM)	WALL THICKNESS (MM)	HOLE SIZE (MM)	MINIMUN FEATURE SIZE	MINIMUN FEATURE SIZE (MM)	SURFACE FINISH	EXTRA	SOURCE
VAT PHOTOPOLYMERIZATION	SLA	POLYMER	$$		3	MED	0.15		0.003679375	145 x 145 x 175	HIGH	0,05	0.25	0.5	HIGH	0.2	HIGH	SLA resins are also a viable option for making snap-fit joints, but they are relatively brittle. Using resins may increase the chances of the snap-fit breaking after repeated use. We recommend durable SLA resin if you print snap-fits with this technology.	hB-EiwAa5
MATERIAL EXTRUSION	FDM	POLYMER	$		3	MED	0.3		0.125	200 x 200 x 200	HIGH	0.3	0.8	2	LOW	2	LOW	FDM is the most cost-efficient way to manufacture snap-fit connectors. While it's definitely effective, the process has lower accuracy than other printing methods. If you choose FDM, we recommend using strain-resistant materials, such as ABS, Nylon and TPU.	hB-EiwAa5
POWDER BED FUSION	SLS	POLYMER	$$		3	MED	0.3		0.0780125	300 x 300 x 300	HIGH	0,1	0.6	1.5	LOW	0.5	MED	SLS printers, on the other hand, are capable of creating decently high-detail parts in a number of different strong materials, like metal, that are perfectly suitable for any number of mechanical purposes.	hB-EiwAa5
	MJF	POLYMER	$$		3	MED	0.3		0.0410096	380 x 284 x 380	HIGH	0,08	0.5		LOW	0.5			hB-EiwAa5
	DMLS/SLM	METAL			14	MED	0.1		0.015625	250 x 250 x 325	HIGH	0.03	1	X	LOW	0.75	ROUGH		55569358
MATERIAL JETTING	POLYJET	POLYMER			7	MED	0.1		0.038318	490 x 391 x 200	HIGH	0.03	X	X	LOW	0.3			
BINDER JETTING	BJ				7	MED	0.5		0.16	300 x 500 x 400	HIGH	0.2	2	1.5	LOW	2			3D PRINT jwKCAjwg
DIRECT ENERGY DEPOSITION	DED					X			0.52	1000 x 800 x	HIGH	0.1	X	X		X			https://w
SHEET LAMINATION	SL					X			0.0064896	256 x 169 x 1	HIGH	0.1	X	X		X			https://w
Carbon Digital Light Synthesis	DLS					MED	0.1		0.0067473	119 x 189 x 30	HIGH	0.1	0.25	0.6	LOW	0.5			PROTOLAB

RELATIVE SCORE VALUE CRITERIA

PERCENTILE CRITERIA FOR TOLERANCE			
HIGH	0.1	LOW PERCENTILE (0.75)	0.3
AVERAGE	0.2083333333	MED (REST)	0.3>X>0.1
LOW	0.3	HIGH PERCENTILE (0.25)	0.1
MEDIAN	0.225		

PERCENTILE CRITERIA FOR LAYER THICKNESS			
MAX	0.3	HIGH PERCENTILE (0.75)	0.15
AVERAGE	0.1228571429	MED (REST)	x
LOW	0.03	LOW PERCENTILE (0.25)	0.065
MEDIAN	0.1		

PERCENTILE CRITERIA FOR BUILDING VOLUME			
HIGH	0.52	HIGH PERCENTILE (0.75)	0.113253125
AVERAGE	0.099488137	MED (REST)	
LOW	0.003679375	LOW PERCENTILE (0.25)	0.008966725
MEDIAN	0.0396638		

PERCENTILE CRITERIA FOR MINIMUN FEATURE			
HIGH	2	HIGH PERCENTILE (0.75)	1.0625
AVERAGE	0.84375	MED (REST)	x
LOW	0.2	LOW PERCENTILE (0.25)	0.45
MEDIAN	0.5		

Figure 2: overview of AM technologies and materials.

	AM TECHNOLOGY & MATERIAL	MATERIAL TYPE	TENSILE STRENGTH (MPa)	TENSILE STRENGTH(HIGH, MED,LOW)	YIELD STRENGHT (MPa)	YOUNG MODULUS (GPa)	ELONGATION AT BREAK (%)	MAX SERVICE TEMP (ºC)	CHEMICAL RESISTANT	UV	FLEXIBLE	TRANSPARENT	WATER RESISTANT	IMPACT RESISTANT GENERAL	HEAT RESISTANCE	IMPACT RESISTANT (NOTCHED J/M)	COST (€)	OTHER	SOURCE
FDM																			
	FDM ABS	POLYMER	45	HIGH	44	2.3	34	89				YES		YES	YES		LOW		https://www.h
	FDM PLA	BIO-POLYMER	65	HIGH	69	2.7	8	190				YES		YES	YES		LOW		edia/2020/01/
	FDM PET	POLYMER	47	HIGH	47	1.5	5										LOW		/en/direct-me
	FDM PETG	POLYMER	50	HIGH	49	1.97	36		YES				YES				LOW		a/catalog/proc
	TPE	POLYMER	5	HIGH	X	X	150	165			YES						LOW		ntent/uploads,
	PP	POLYMER	32	HIGH				100					YES		YES		LOW		oads/2020/10/
	PC	POLYMER	72	HIGH										YES	YES		LOW		https://www.
	TPU	POLYMER	59	HIGH	9	3.1	587				YES						LOW		
	PEEK	POLYMER	105	HIGH		4.1	30	340	YES						YES		LOW	VERY DIFFICULT TO PRINT	pliki/downloa
	PVDF	POLYMER	50	HIGH		2.1	50	160	YES	YES						X	LOW		ducts/pvdf-3d-
	ASA	POLYMER	45	HIGH	47	2.4	35	105		YES				YES	YES		LOW		o-content/uplo
	NYLON 12	POLYMER	48	HIGH		3.8	4	176						YES	YES		MED		
SLA																			
	Formlabs Standard Resin	POLYMER	65	HIGH		2.8	6.2									25	MED		
	Formlabs Grey Pro Resin	POLYMER	61	HIGH		2.6	13									18.7	MED		
	Formlabs Clear Resin	POLYMER	65	HIGH		2.8	6.2					YES				25	MED		
	Formlabs Durable Resin	POLYMER	31.8	HIGH		1.26	49							YES		109	MED		
	Formlabs High Temp Resin	POLYMER	58.3	HIGH		2.8	3.3									18.2	HIGH		
	Formlabs Tough Resin 2000	POLYMER	46	HIGH		2.2										40			
	Formlabs Rigid Resin 4000	POLYMER	69	HIGH		3.4	5.3									X	HIGH		
	Accura ClearVue	POLYMER	46	HIGH			7					YES				67			
	Accura Xtreme White 200	POLYMER	50	HIGH		2.6	20						YES	YES		66		SNAP FITS, INJECTION MOULDED	00.com/mater
	Accura 25	POLYMER	38	HIGH		1.66	20									24		SNAP FITS, INJECTION MOULDED	ems.com/mat
	Formlabs Flexible 80A	POLYMER	8.7	HIGH			120				YES						MED		s.com/datash
SLS																			
	SLS Nylon (PA 12)	POLYMER	50	HIGH	x	1.8	36	180	YES	YES					YES	32	MED	Strong, lowest cost,1 quality parts	2001447-TDS-
	NYLON 12 GF	POLYMER	44	HIGH	X	X	3	X	X	X	X	X	X	X	YES	X	X		
	SLS.Jabil PLA 3110P,	BIO-POLYMER	26	HIGH	X	X	X	X	X	X	X	X	X	X	X	X	X	More sustainability that alternative SLS materials.	
	SLS.Polypropylene (PP)	POLYMER	28	HIGH	X	X	X	X	X	X	X	X	X	X	X	X	X		etry.eu/en/sls-
	SLS. Alumide® / Nylon 12 (PA 12)	METALIC	48	HIGH	X	3.6	4	176		YES				YES	YES	4.6 kJ/m²	LOW	igh rigidity • High dimensional accuracy • High thermal conductivity • Machinability	etry.eu/en/sls-
	SLS Nylon 11 (EX) (Rilsan® Invent Natural):	BIO-POLYMER	45	HIGH	X	X	45%	X	X	X	X	X	X	X	X	X	X	100% bio-based	om/product/t-
	SLS. FLEX TPU	POLYMER	X	HIGH	x	x	x	x	x	x	YES	X	X	X	X	4.9 kJ/m²	X		etry.eu/en/sls-
	Bluesint PA 12	BIO-POLYMER	45	HIGH	X	X	17	X	X	X	X	X	X	X	X	X	X	100% RECYCLABLE	
MJF																		alternative for **injection moulded**	https://www.
	HP PA 12 (Nylon 12)	POLYMER	48	HIGH	48	1.8	20	175	YES				YES	YES	YES	x			uploads/2019/
	TPU 88A	POLYMER	9	HIGH	8	0.08	220	120			YES					999		f parts requiring shock absorption, energy return or flexibility.	uploads/2020/

60<X

60<X<200

200<X

PERCENTILE CRITERIA FOR STRENGHT			
MAX	105	HIGH PERCENTILE (0.75)	58.475
MEAN	47.03	MED (REST)	X
MIN	5	LOW PERCENTILE (0.25)	42.5
MEDIAN	47.5		
MODE	45		

Appendix C

5. OVERVIEW ON AVAILABLE AM TECHNOLOGIES

Table 1: overview on available am technologies.

	BINDER JETTING (BJT)	DIRECT ENERGY DEPOSITION	MATERIAL EXTRUSION: (FDM)	MATERIAL JETTING (MJT)
DESCRIPTION	BJT produces parts by depositing a binding agent selectively on a powder bed. Powder is spread on the build platform and a print head sprays a binder agent onto specific. A notable difference is that BJT does not require heat to fuse the material. (Loughborough University, n.d)	DED technique deposits melted material onto the specified surface with a nozzle. The process is similar in principle to material extrusion. (Loughborough University, n.d)	Material extrusion of fused deposition modelling (FDM) is a process where the heated and melted material filaments are extruded from a nozzle and deposited layer by layer in a building platform. (3D Hubs, n.d.)	MJT operates like a 2D printer. A printhead dispenses droplets of photosensitive layer by layer, which solidifies under ultraviolet (UV) light. (Loughborough University, n.d)
SPECIFICATION	Build volume: Metal: 400 x 250 x 250 mm, Full-colour: 200 x 250 x 200 mm, Sand: 800 x 500 x 400. (Loughborough University, n.d)	Build volume: 1000 x 800 x 650 mm (3D Hubs, n.d.)	Build volume: Large (e.g., 900 x 600 x 900 mm); Medium (e.g., 200 x 200 x 200 mm) (3D Hubs, n.d.)	Build volume: 380 x 250 x 200 mm (up to 1000 x 800 x 500 mm) (3D Hubs, n.d.)
	Support: Not required	Support:	Support: Not always required (3D Hubs, n.d.)	Support: Always required. (3D Hubs, n.d.)
	Materials: Metals, Ceramics (sand)	Materials: Metals and not polymers or ceramics.	Materials: Polymers such as ABS, Nylon, PC, PC, AB	Materials: Acrylic photopolymers (thermoset)
	Dimensional accuracy: Metal: ± 0.2 mm Full-colour: ± 0.3 mm Sand: ± 0.3 mm	Dimensional accuracy:	Dimensional accuracy: ± 0.5 mm generally.	Dimensional accuracy: ± 0.1% (lower limit of ± 0.05 mm)
ADVANTAGES	Produces complex, high-precision parts. Fast and cost-effective. Allows the creation of multi-color parts, especially non-metallic ones. Can be easily integrated with most traditional foundry processes.	Offers of high quality, functional parts	Widespread and inexpensive process	High accuracy and low waste generated. Use of multiple materials and colouring.

	(Loughborough University, n.d)			
DISADVANTAGE	Needs to be infiltrated and sintered which causes shrinkage. Components before post-processing are fragile and can crumble. Low mechanical properties of printed components.	Finishes can vary depending on paper or plastic material but may require post processing to achieve desired effect. Limited material use Fusion processes require more research.	The nozzle radius limits and reduces the final quality. Accuracy and speed are low when compared to other processes and accuracy of the final model is limited to material nozzle thickness.	A high accuracy can be achieved but materials are limited and only polymers and waxes can be used. MJ materials are photosensitive, and their mechanical properties degrade over time.

Table 2: overview on available am technologies.

	POWDER BED FUSION (PBF)	SHEET LAMINATION	VAT PHOTOPOLYMERIZATION
DESCRIPTION	Powder Bed Fusion (PBF) technology uses a thermal energy (laser or electron beam) to layer by layer melt the powder material, (Xometry, n.d.)	The technology pre-cuts sheets of material and stack them in the horizontal cross section of the part to be constructed. (3D Hubs, n.d.)	The technology utilises a vat of liquid photopolymer resin. The ultraviolet (UV) light is used to cure and harden the resin where required to build the geometry. (Loughborough University, n.d)
SPECIFICATIONS	Build volume: 381 x 330 x 457 mm (Loughborough University, n.d.)	Build volume: 256 x 169 x 150 mm (Loughborough University, n.d.)	Build volume: Up to 145 x 145 x 175mm-desktop 1500 x 750 x 500mm-Industrial
	Support: Not required (3D Hubs, n.d.)	Support: Not necessary (3D Hubs, n.d.)	Support: Yes (3D Hubs, n.d.)
	Materials: Ceramic, metal, and plastic, in the form of powder, in a layer-by-layer fashion to build a 3D object. (Xometry, n.d.)	Materials: Papers, most polymers, fibre-reinforced polymers, ceramics, and any metal. (3D Hubs, n.d.)	Materials: Plastics and Polymers. (3D Hubs, n.d.)
	Dimensional accuracy: ± 0.3 mm	Dimensional accuracy: Not specified.	Dimensional accuracy: Average of ± 0.3 mm

	(3D Hubs, n.d.)		(Xometry, n.d.)
ADVANTAGES	Good mechanical properties. Ideal for functional parts and prototypes. Requires no support, complex geometries can be easily produced. Excellent for small to medium batch production. Remaining unused powder is collected and can be reused. (3D Hubs, n.d.)	High speed of production and low cost and material handling.	High level of accuracy and good finish Quick process (Loughborough University, n.d)
DISADVANTAGES	Only industrial systems are currently widely available, therefore lead times are longer than other technologies. Components have a grainy surface finish and internal porosity that may require post-processing for smooth surface and water resistance. Large flat surfaces and small holes cannot be printed accurately. (3D Hubs, n.d.)	Results require postprocessing to achieve the desired effect. Limited material choice. The adhesive used determines the strength and integrity of the component (Krar and Gill, 203) Requires more research to further advance the process into a more mainstream positioning. Low Resolution (Xometry, 2023)	Components are brittle and not suitable for functional prototypes. Mechanical properties and visual appearance of parts degrade over time when exposed to sunlight. Support structures are always required as well as post-processing to remove the visual marks left on the part. (3D Hubs, n.d.)

Appendix D

6. SPARE PARTS ATTRIBUTES AND AM SUITABILITY

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Table 314: Overview of identified spare part and supply chain attributes and how they reflect on AM adoption.

SPARE PART ATTRIBUTES		DESCRIPTION AND AM SUITABILITY
DEMAND UNCERTAINTLY	High demand uncertainty	Affects long-term spare parts management prediction. Excess stock leads to storage inefficiency, increased costs, and obsolescence risk. Conversely, sudden high demand disrupts response time and raises production restart costs (Knofius et al., 2016; Khajavi et al., 2014) AM can offer stability as its production can be sustained 24 hours a day, seven days a week and the cost is less subjected to the number of batches required, additionally, the digitalisation of stock reduces the risk of physical excess stock (Knofius et al., 2016)
	Low frequency demand / Slow moving components	Low-frequency demand component leads to slow-moving parts, storage in storage inefficiency, increased costs, and obsolescence risk (Knofius et al., 2016). Slow-moving components refers to pieces of inventories that are kept in storage for an extended period with little to no usage (Fiix, n.d.). AM can translate slow-moving parts to an on-demand and digital printing solution, thus reducing storage inefficiency (Sasson & Johnson, 2016).
	High demand	During high demand, companies may struggle to supply all the required spare parts due to manufacturing lead times or the limited production capacity of the current manufacturing structure. AM offers the opportunity to support the manufacturing process by allocating part of the production to AM suppliers, thus providing increased responsiveness to the company (Cardea et al., 2020)
PRODUCTION	High part value	Due to the high cost of AM printing, it is not economical to transition from low-cost manufacturing (e.g., injection moulded) to 3D printing. More expensive, 3D printing requires parts to hold higher value to be profitable (Holmström et al., 2010).
	High Design complexity	AM process offers greater manufacturing freedom for complex geometries (e.g., Topology optimized parts). Additionally, the manufacturing process remains consistent regardless of part complexity as there is no required additional tooling such as moulds. (Garrett, 2014; Cozmei & Caloian, 2012).
	Low volume manufacturing	AM is best suited for small batch production, offering a more affordable alternative to traditional manufacturing processes, as these require expensive tooling such as moulds in the case of Injection Moulding (Sasson & Johnson, 2016; Cardeal et al., 2020).
	Part customization	Traditional manufacturing has notable cost variations between making a single custom object and mass production. In contrast, AM maintains a consistent unit cost, facilitating mass customization. Sharing a production line for custom/low-volume and high-volume parts can be disruptive. (Garrett, 2014).
SUPPLY CHAIN	High supply risk	Supply chain disruption scenarios like COVID-19 or companies required to provide spare parts for a certain period, necessitate supply chain security. Another scenario involves mandatory volume orders resulting in excess stock, increased cost and obsolescence risk. (Knofius et al., 2016).

		AM offers companies a safeguard in risk scenarios to continue the supply of spare parts to clients until the regular manufacturing process can be incorporated once more (Formlabs, SLS case studies)
	High responsiveness	AM enables the offers to reduce repair lead time by local on-demand printing services. An example is the case of Siemens (2015), reducing up to 90% of the repair lead time and 30 % of the cost through AM use (Knofius et al., 2016). Currently, companies exhibit high responsiveness during emergencies, often relying on costly emergency shipments or excess stock (Walter et al., 2004)
	High cost	Where production cost, inventory cost and transport cost can pose a challenge, AM offers to print on demand locally and at a lower cost for a limited number of parts. Thus, reducing transportation, manufacturing, and stocking cost (Knofius et al., 2016)

Appendix E

Figure 2: spare parts availability overview.

C	D	E	J	K	L	M	N	O
PART CLASSIFICATION AND ELIGIBILITY EVALUATION								
NOTES								
ASSEMBLY	NAME	COMPONENT DATA	REPLACEMENT AVAILABILITY	REPLACEMENT AVAILABILITY				
				OFFICIAL PHILIPS	COST OFFICIAL	ALTERNATIVE	COST ALTERNATIVE	LINK
				LINK TO OFFICIAL PHILIPS SPARE	https://www.philips.nl/c-m-ho/accessoires-voor-stofzuigers-dweilen/nieuwste#availabilit			
C1	SPEEDPRO							
	sp.Chassis			YES, AS ASSEMBLY	150			PHILIPS
	Exhaust fan							
	Motor assy							
	Johnson motor (type:HC685LG)							
	Johnson motor (type:HC685LG) with chokes							
	Diffuser bottom housing							
	Screws							
	Fan assy							
	Fan top							
	Fan bottom							
	Fan bearing							
	Fan cover							
	sp.Inlet sealing ring			YES, AS ASSEMBLY	150			PHILIPS
	PCB with 2 chokes							
	Motor wires AWG 18, 160mm							
	JST VHR-2N connector							
	Motor wire sealing							
	sp.Motor front buffer			YES, AS ASSEMBLY	150			PHILIPS
	sp.Motor inlet cover/Grill			YES, AS ASSEMBLY	150			PHILIPS
	Suspension wire spring							
	Screws							
	sp.Release button			YES, AS ASSEMBLY	150			PHILIPS
	sp.Release hook			YES, AS ASSEMBLY	150			PHILIPS
	Release spring							
	sp.Inlet piece			YES, AS ASSEMBLY	150			PHILIPS
	sp.Inlet seal/rubber			YES, AS ASSEMBLY	150			PHILIPS
	Small fluff strip							
	Female connector							
	Female connector top							
	Tube wire harness							
	AWG24 wires (400mm)							
	contacts							
	JST PHR-3 connector							
	sp.Side panel left			YES, AS ASSEMBLY	150			PHILIPS
	sp.Side panel right			YES, AS ASSEMBLY	150			PHILIPS
	sp.Rim			YES, AS ASSEMBLY	150			PHILIPS
CHASIS	sp.Rear cover			YES, AS ASSEMBLY	150			PHILIPS
	sp.Anti slip rubber			YES, AS ASSEMBLY	150			PHILIPS
	Anti slip tape.							
	Charging plate assy							
	sp.Charging cover			YES, AS ASSEMBLY	150			PHILIPS
	Metal disk charging							
	Contact pin positive							
	Contact pin negative							
	Ring faston charging							
	Charging wire harness with fuse							
	Contact pin							
	Wire AWG 24, 300mm							
	JST PHR-2N connector							
	Screws							
	Inlet Filter							
	Overmold sealing rim							
	Inlet filter separate 410							
	Inlet filter separate 410 Freudenberg							
	Foam filter 45 PPI							
	Foam filter 90 PPI							
	Foil wrapped Battery pack 18V							
	sp.PCB frame			YES, AS ASSEMBLY	150	NO		
	Main PCBA with data logging							
	Screws							
	SW UI slider assy							
	Skywalker UI PCBA							
	UI PCB (5LED, 2Switch)							
	Wires AWG 24, 250mm							
	JST PHR-8 connector							
	sp.Slider frame			YES, AS ASSEMBLY	150			PHILIPS
	Spring							
	sp.Internal slider			YES, AS ASSEMBLY	150			PHILIPS
	Diffuser foil							
	sp.Window			YES, AS ASSEMBLY	150			PHILIPS
	sp.UI cover			YES, AS ASSEMBLY	150			PHILIPS
	sp.Slider button			YES, AS ASSEMBLY	150			PHILIPS
	sp.Handle cover			YES, AS ASSEMBLY	150			PHILIPS
	Adapter + disk 25V Euro plug							
	Adapter + disk 29V Euro plug							
	Wall mount plugs							
	Wall mount screws							
	small Plastic bag							
	Wall Mount							
	Bucket assy							
	sp.Bucket			YES, AS ASSEMBLY	66,59	YES, AS PART	30	ALIEXPRESS
	sp.Dust outlet			YES, AS ASSEMBLY	66,59	YES, AS ASSEMBLY	30	ALIEXPRESS
	sp.Bucket inlet sealing			YES, AS ASSEMBLY	66,59	YES, AS ASSEMBLY	30	ALIEXPRESS
	sp.Inlet sealing lock			YES, AS ASSEMBLY	66,59	YES, AS ASSEMBLY	30	ALIEXPRESS
	sp.Sealing			YES, AS ASSEMBLY	66,59	YES, AS ASSEMBLY	30	ALIEXPRESS
	sp.valve			YES, AS ASSEMBLY	66,59	YES, AS ASSEMBLY	30	ALIEXPRESS
	Valve seat							
	valve axle							
	sp.Vortex finder			YES, AS PART	10	YES, AS ASSEMBLY	30	ALIEXPRESS
	sp.Bucket lid			YES, AS PART	13	YES, AS SUB-ASSEMBLY	10	PHILIPS
	Tampon print							
	sp.Bucket lid sealing			YES, AS ASSEMBLY	13	YES, AS ASSEMBLY	30	ALIEXPRESS
	sp.VORTEX CAP			YES, AS ASSEMBLY	13	YES,AS PART	10	ALIEXPRESS
	Assy ACTIVE nozzle							
	sp.SW passive nozzle soleplate incl Squeegee			YES, AS ASSEMBLY	30	YES, AS ASSEMBLY	36	ALIEXPRESS
	sp.SW passive nozzle Airchannel insert			YES, AS ASSEMBLY	30	YES, AS ASSEMBLY	36	ALIEXPRESS
	Squeegie							
	sp.Front Wheel Bearing			YES, AS ASSEMBLY	30	YES, AS ASSEMBLY	36	ALIEXPRESS
	Front Wheel Axle (22.5x3mm)							
	sp.Front Wheel Base			YES, AS ASSEMBLY	30	YES, AS ASSEMBLY	36	ALIEXPRESS
	sp.Front Wheel Over Mold			YES, AS ASSEMBLY	30	YES, AS ASSEMBLY	36	ALIEXPRESS
	Weight							
	Brush holder left							
	Side brush left							
	Brush holder right							
	Side brush right							
	sp.SW passive nozzle top cover			YES, AS ASSEMBLY	30	YES, AS ASSEMBLY	36	ALIEXPRESS
	hot foil (20x70mm)							
	Tampon print							
	Screw 3,5x15							
	Fluff strip (84x8mm)							
	sp.Stretch Hose			YES, AS ASSEMBLY	30	YES, AS ASSEMBLY	36	ALIEXPRESS
	assy SW passive nozzle tube interface							
	sp.Tube interface aqua			YES, AS ASSEMBLY	30	YES, AS ASSEMBLY	36	ALIEXPRESS
	sp.Bearing			YES, AS ASSEMBLY	30	YES, AS ASSEMBLY	36	ALIEXPRESS

wire assy to motor							
side brush							
Drive assy service unit							
drive motor							
spM.motor gear			YES, AS ASSEMBLY	60			
spM.brush gear			YES, AS ASSEMBLY	60			
spM.belt			YES, AS ASSEMBLY	60	YES, AS SUB ASSEMBLY	22	ALIEXP RESS
spM.transmission housing			YES, AS ASSEMBLY	60	YES, AS SUB ASSEMBLY	22	ALIEXP RESS
spM.brush drivehead			YES, AS ASSEMBLY	60	YES, AS SUB ASSEMBLY	22	ALIEXP RESS
ball bearing							
ball bearing spacer							
nozzle exhaust foam							
male connector							
Tampon print/Hot Foil							
protective flap blister							
Screws							
rubber band							
protective bag nozzle							
wire clamp							
BRUSH							
spM.brush core			YES, AS SUB ASSEMBLY	20	YES, AS SUB ASSEMBLY	14	LIEXPRES
tuft implant							
spM.side lock cap			YES, AS SUB ASSEMBLY	20	YES, AS SUB ASSEMBLY	14	LIEXPRES
brush bearing							
spM.side lock lever			YES, AS SUB ASSEMBLY	20	YES, AS SUB ASSEMBLY	14	LIEXPRES
brush lines							
brush steel shaft							
spM.brush core disc_drive side			YES, AS SUB ASSEMBLY	20	YES, AS SUB ASSEMBLY	14	LIEXPRES
spM.brush core disc_end cap side			YES, AS SUB ASSEMBLY	20	YES, AS SUB ASSEMBLY	14	LIEXPRES
WHEELS							
spM.front wheel core			YES, AS ASSEMBLY	80			
spM.overmold front wheel			YES, AS ASSEMBLY	80			
front wheel axle							
spM.front wheel bearing right			YES, AS ASSEMBLY	80			
spM.front wheel bearing left			YES, AS ASSEMBLY	80			
BACK WHEELS							
spM.Rear Wheel core			YES, AS ASSEMBLY	80	YES, AS SUB ASSEMBLY	22	ALIEXP RESS
spM.overmould rear wheel			YES, AS ASSEMBLY	80	YES, AS SUB ASSEMBLY	22	ALIEXP RESS
spM.rear wheel axle			YES, AS ASSEMBLY	80	YES, AS SUB ASSEMBLY	22	ALIEXP RESS
spM.rear wheel bearing			YES, AS ASSEMBLY	80	YES, AS SUB ASSEMBLY	22	ALIEXP RESS
spM.rear wheel bearing lock			YES, AS ASSEMBLY	80	YES, AS SUB ASSEMBLY	22	ALIEXP RESS
TUBE ASSY							
Tube							iatrio-cor
spM.tube end			YES, AS ASSEMBLY	30	YES, AS SUB ASSEMBLY	15	LIEXPRES
spM.tube inlet			YES, AS ASSEMBLY	30	YES, AS SUB ASSEMBLY	15	LIEXPRES
spM.tube inlet cover bottom			YES, AS ASSEMBLY	30	YES, AS SUB ASSEMBLY	15	LIEXPRES
spM.tube inlet cover top			YES, AS ASSEMBLY	30	YES, AS SUB ASSEMBLY	15	LIEXPRES
spM.tube end cover			YES, AS ASSEMBLY	30	YES, AS SUB ASSEMBLY	15	LIEXPRES
spM.tube unlock button			YES, AS ASSEMBLY	30	YES, AS SUB ASSEMBLY	15	LIEXPRES
spM.tube unlock spring			YES, AS ASSEMBLY	30	YES, AS SUB ASSEMBLY	15	LIEXPRES
female connector							
female connector top							
male connector							
Wiring assy							
tube wire plug							
tube seal							
inlet seal							
SPM.integrated brush			YES, AS PART	6,99			o/FC8093
Tuft implant for integrated brush							o/FC8093

sp.Tube interface aqua			YES, AS ASSEMBLY	30	YES, AS ASSEMBLY	36	ALIEXP RESS
sp.Bearing			YES, AS ASSEMBLY	30	YES, AS ASSEMBLY	36	ALIEXP RESS
sp.Joint			YES, AS ASSEMBLY	30	YES, AS ASSEMBLY	36	ALIEXP RESS
sp.Bearing Half left			YES, AS ASSEMBLY	30	YES, AS ASSEMBLY	36	ALIEXP RESS
sp.Bearing Half left			YES, AS ASSEMBLY	30	YES, AS ASSEMBLY	36	ALIEXP RESS
sp.Joint cap aqua			YES, AS ASSEMBLY	30	YES, AS ASSEMBLY	36	ALIEXP RESS
sp.Tube interface cap top			YES, AS ASSEMBLY	30	YES, AS ASSEMBLY	36	ALIEXP RESS
sp.Tube interface cap bottom			YES, AS ASSEMBLY	30	YES, AS ASSEMBLY	36	ALIEXP RESS
sp.Release button			YES, AS ASSEMBLY	30	YES, AS ASSEMBLY	36	ALIEXP RESS
sp.Release button spring			YES, AS ASSEMBLY	30	YES, AS ASSEMBLY	36	ALIEXP RESS
Screw 2,5*5							
Screw 2,5*8							
Screw 3,5*15							
sp.Rear Wheel bearing							
Hinge Axle (15,5x4mm)							
sp.Rear Wheel Base			YES, AS ASSEMBLY	30	YES, AS ASSEMBLY	36	ALIEXP RESS
sp.Rear Wheel Over Mold			YES, AS ASSEMBLY	30	YES, AS ASSEMBLY	36	ALIEXP RESS
TOTAL	122						
CUT OFF CRITERIA	0						
RESULT	122						
SPEEDPRO MAX							
NOZZLE BODY							
spM.soleplate			YES, AS ASSEMBLY	60			FC6904 F
spM.soleplate overmold			YES, AS ASSEMBLY	60			FC6904 F
spM.Top housing left			YES, AS ASSEMBLY	60			FC6904 F
spM.Top housing right			YES, AS ASSEMBLY	60			FC6904 F
spM.Window			YES, AS ASSEMBLY	60			FC6904 F
spM.Top cover			YES, AS ASSEMBLY	60			FC6904 F
spM.exhaust bottom			YES, AS ASSEMBLY	60			FC6904 F
spM.pcb cover			YES, AS ASSEMBLY	60			FC6904 F
flex hose							
hinge bearing							
hinge shaft							
spM.joint			YES, AS ASSEMBLY	60			FC6904 F
spM.tube interface			YES, AS ASSEMBLY	60			FC6904 F
spM.lock ring left			YES, AS ASSEMBLY	60			FC6904 F
spM.lock ring right			YES, AS ASSEMBLY	60			FC6904 F
spM.bearing disk			YES, AS ASSEMBLY	60			FC6904 F
spM.joint cap			YES, AS ASSEMBLY	60			FC6904 F
spM.tube interface cap top			YES, AS ASSEMBLY	60			FC6904 F
spM.tube interface cap bottom			YES, AS ASSEMBLY	60			FC6904 F
spM.tube unlock button			YES, AS ASSEMBLY	60			FC6904 F
tube unlock spring							
spM.intake rear left			YES, AS ASSEMBLY	60			FC6904 F
spM.intake rear right			YES, AS ASSEMBLY	60			FC6904 F
spM.front bumper			YES, AS ASSEMBLY	60			FC6904 F
Nozzle PCB							
wire assy to PCB							
wire assy to motor							
side brush							
Drive assy service unit							
drive motor							
spM.motor gear			YES, AS ASSEMBLY	60			
spM.brush gear			YES, AS ASSEMBLY	60			
spM.belt			YES, AS ASSEMBLY	60	YES, AS SUB ASSEMBLY	22	ALIEXP RESS
spM.transmission housing			YES, AS ASSEMBLY	60	YES, AS SUB ASSEMBLY	22	ALIEXP RESS
spM.brush drivehead			YES, AS ASSEMBLY	60	YES, AS SUB ASSEMBLY	22	ALIEXP RESS
ball bearing							

Tuft implant for integrated brush							o/FC8093	
Tube screw							o/FC8093	
tube bag							o/FC8093	
MAIN BODY								
spM.panel left			YES, AS ASSEMBLY	200				
spM.panel right			YES, AS ASSEMBLY	200				
spM.Handle loop			YES, AS ASSEMBLY	200				
handle insert								
spM.Handle panel			YES, AS ASSEMBLY	200				
spM.UI window			YES, AS ASSEMBLY	200				
spM.visual cap			YES, AS ASSEMBLY	200				
spM.visual cap inner			YES, AS ASSEMBLY	200				
spM.Wall friction interface			YES, AS ASSEMBLY	200				
Wall friction interface tape								
spM.bucket release button			YES, AS ASSEMBLY	200				
spM.bucket release lever			YES, AS ASSEMBLY	200				
bucket release spring								
spM.Chasiss			YES, AS ASSEMBLY	200				
ESD spring								
spM.handheld inlet			YES, AS ASSEMBLY	200				
spM.anti scratch strip			YES, AS ASSEMBLY	200				
spM.charging plate			YES, AS ASSEMBLY	200				
spM.exhaust grill			YES, AS ASSEMBLY	200				
SPM motor badgesp			YES, AS ASSEMBLY	200				
spM.MOTOR SUPPORT FRAME			YES, AS ASSEMBLY	200				
screw cone								
spM.sound reflector			YES, AS ASSEMBLY	200				
sealing tape								
exhaust foam								
spM.frame top			YES, AS ASSEMBLY	200	YES, AS SUB ASSEMBLY	120	Philips-s	
spM.hook insert			YES, AS ASSEMBLY	200				
wire main PCBA to batt pack								
contact pin positive								
contact pin negative								
contact flange								
UI PCBA 18V								
UI PCBA 25V								
insulation tape								
UI PCBA service assy 18V								
BLDC 25V Electronics								
spM.external slider			YES, AS ASSEMBLY	200				
silder spring holder								
internal slider								
Slider blade spring								
UI led frame								
spM.seal inlet			YES, AS ASSEMBLY	200				
UI printed mylar								
female connector								
female connector top								
spM.Connection holder battery pack			YES, AS ASSEMBLY	200	YES, AS PART	23,74	ict/view/	
handheld typeplate								
Screws								
handheld bag								
MOTOR ASSY								
spM.Front suspension / seal/ MOTOR RUBBER			YES, AS ASSEMBLY	200	YES, AS SUB ASSEMBLY	120	Philips-s	
spM.motor support frame seal			YES, AS ASSEMBLY	200	YES, AS SUB ASSEMBLY	120	Philips-s	
spM.rear suspension			YES, AS ASSEMBLY	200	YES, AS SUB ASSEMBLY	120	Philips-s	
BLDC 18V								
motorfoam								

wire charger to motor PCBA								
ESD lead wire								
wire main PCBA to motor PCBA								
BUCKET ASSY								
spM.bucket dust inlet			YES, AS ASSEMBLY	45	YES, AS SUB-ASSEMB	30	ALIEXPRESS	
spM.seal bucket inlet			YES, AS ASSEMBLY	45	YES, AS SUB-ASSEMB	30	ALIEXPRESS	
spM.bucket internal seal			YES, AS ASSEMBLY	45	YES, AS SUB-ASSEMB	30	ALIEXPRESS	
spM.return valve			YES, AS ASSEMBLY	45	YES, AS SUB-ASSEMB	30	ALIEXPRESS	
spM.bucket			YES, AS ASSEMBLY	45	YES, AS SUB-ASSEMB	30	ALIEXPRESS	
spM.Bucket Dust Outlet			YES, AS ASSEMBLY	45	YES, AS SUB-ASSEMB	30	ALIEXPRESS	
ESD bucket screw								
valve shaft								
spM.bucket lid			YES, AS ASSEMBLY	12.99	YES, AS SUB-ASSEMB	28,11	ALIEXPRESS	
spM.bucket lid insert GOLD			YES, AS ASSEMBLY	12.99	YES, AS SUB-ASSEMB	28,11	ALIEXPRESS	
spM.CAP LETTERS			YES, AS ASSEMBLY	12.99	YES, AS SUB-ASSEMB	28,11	ALIEXPRESS	
spM.CAP TOP			YES, AS ASSEMBLY	12.99	YES, AS SUB-ASSEMB	28,11	ALIEXPRESS	
spM.bucket lid seal			YES, AS ASSEMBLY	12.99	YES, AS SUB-ASSEMB	28,11	ALIEXPRESS	
Hot foil plate								
vortex 10 hot foil								
bucket filter frame								
FILTER FOAM								
FILTER PULL LIP								
filter layer								
spM.Vortex finder			YES, AS ASSEMBLY	66,59	YES, AS PART	10	:2d-1cdaa	
Battery Pack 18V								
Battery Pack 25V								
Battery Pack plastic housing front + back								
battery pack housing BACK								
battery pack HOUSING FRONT								
Battery Pack PCB 18V								
Battery Pack BMS PCB 25V								
Cell 18650 18V								
Cell 18650 25V								
steel contacts for appliance								
battery contact spring								
battery wires to BMS pcb								
4-cell holder								
3-cell holder								
batt pack typeplate								
HOUSING WALL MOUNT ASSY								
Housing wall mount								
wall mount bag								
Charging disk assy								
charger disk top								
charger disk bottom								
disk wire holder								
disk contact outer								
disk contact inner								
charging disk magnet								
Adapter + disc 25.2V								
Adapter + disc 18V								
Charger bag								
small bag screws+plugs								
TUBE ASSY								
MTB_TUBE_INTERFACE								
MTB_MALE_CONNECTOR								
MTB_TUBE_UNLOCK_BUTTON								
MTB_TUBE_UNLOCK_SPRING								
MTB_TUBE_END_COVER								
NOZZLE_WINDOW								
NOZZLE_TOP								
NOZZLE_TOP_COVER								
NOZZLE_BOTTOM								
RELEASE_BUTTON								

Appendix F

7. Components' printing

The process conducted for the printing of components follows company experts' process and OEM established guidelines (Formlabs, Guide to SLS printing). Supplier-requested manufacturing of components and materials are not presented as these were not shared by the company.

Technology & material selection

Company-available Formlabs Fuse 1+30W SLS is exclusively equipped with Nylon 12 Glass-filled (GF 12) due to company policy. To address the need for flexible materials and alternative rigid polymers for further understanding of SLS processes, a direct company supplier is reached for Nylon 12 (PA 12) material, offering major ductility than GF 12, Thermoplastic Elastomer (TPE) for more flexible components and Thermoplastic Polyurethane (TPU) for stiffer rubber-like components.

Software & settings

Siemens NX is used to access product CAD models, which are later exported as Stl. files. The files are imported into Formlabs *PreForm* software. For the printing settings, *One-Click Print* mode is used to automatically orient models in the print bed. The file is then transferred to the Formlabs Fuse 1+30W SLS printer via Wi-Fi, where the print job is accepted. The specified refresh rate for every printing job is set to the established 30% standard at the company.

Printing & part recovery

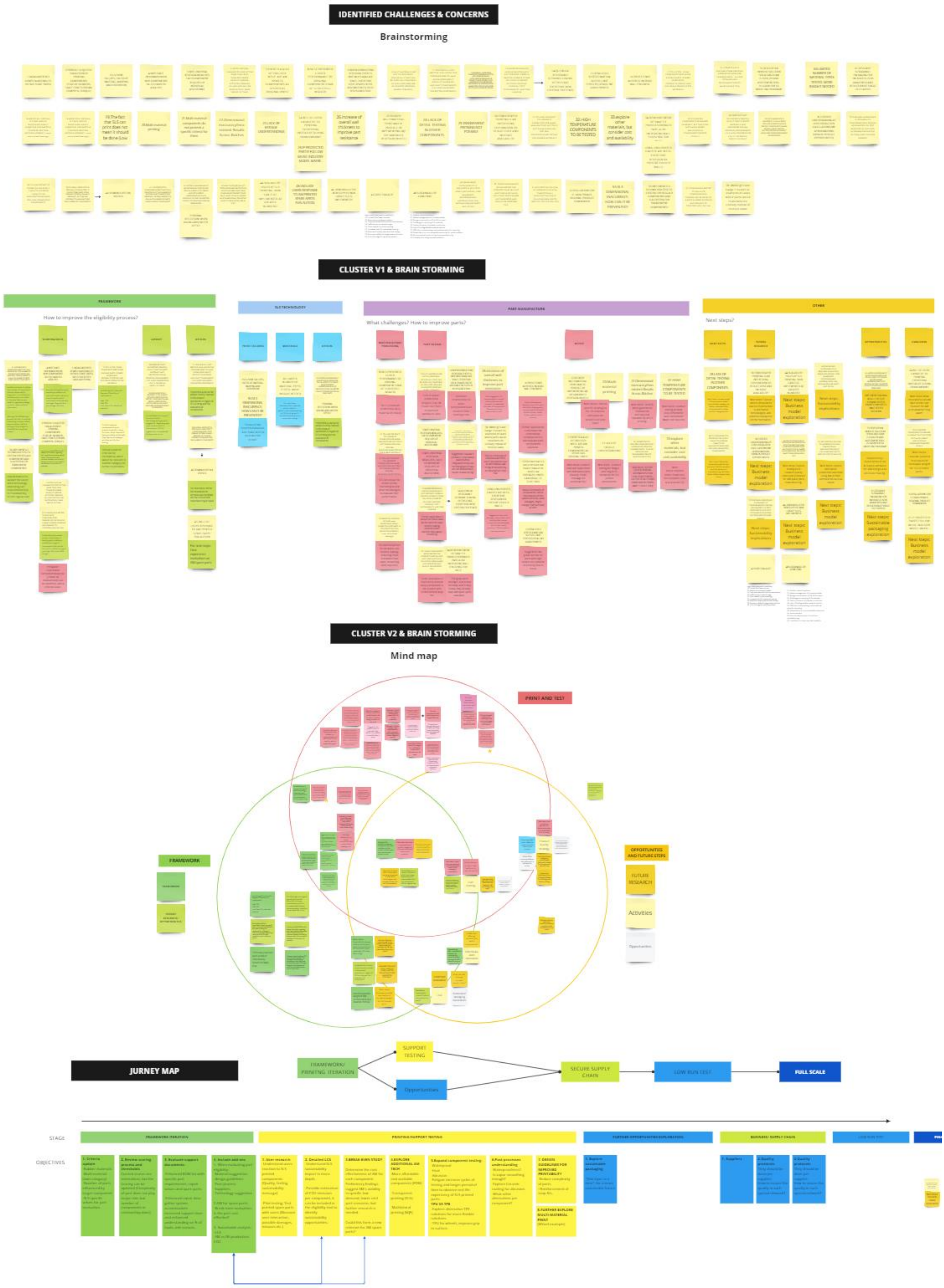
Once the printing is conducted, the build chamber is extracted from SLS printers and transferred to the Fuse Sift Powder Recovery Station. Here, the building chamber resulting material or "Cake" is uploaded and the part recovery is conducted. For that, hands and brushes are used to separate the printed components from the excess material, which is vacuumed and collected for later use. The printed components present the Surface Armour. For that, a sandblasting station is used to clear components' surfaces and cavities from excess material.

Figure 22: Overview of printing process.

Appendix G

FRONT WHEEL BEARINGS										
MEASURE NUMBER	1		2		3		4		5	
REFERENCE CAD (MM)	3.00		3.00		2.40		7.20		5.40	
PRINTED (MM)	GF 12	PA 12	GF 12	PA 12	GF 12	PA 12	GF 12	PA 12	GF 12	PA 12
SAMPLE 1	2.67	3.08	2.38	2.90	2.38	2.13	6.90	7.04	5.31	5.38
SAMPLE 2	2.80	2.96	2.94	2.89	2.22	2.38	7.27	7.13	5.25	5.40
SAMPLE 3	3.45	3.02	3.36	2.80	2.41	2.24	7.52	6.92	5.53	5.31
MEAN OF DIFFERENCE	0.03	0.02	0.11	0.14	0.06	0.15	0.03	0.17	0.04	0.04
MEAN OF REAL VALUES	2.97	3.02	2.89	2.86	2.34	2.25	7.23	7.03	5.36	5.36
INTEGRATED BRUSH										
MEASURE NUMBER	1		2		3		4		5	
REFERENCE CAD (MM)	9.00		4.60		2.40		7.20		5.40	
PRINTED (MM)	GF 12	PA 12	GF 12	PA 12	GF 12	PA 12	GF 12	PA 12	GF 12	PA 12
SAMPLE 1	8.58	9.32	4.60	4.28	2.38	2.13	6.90	7.04	5.31	5.38
SAMPLE 2	8.65	9.24	4.32	4.42	2.22	2.38	7.27	7.13	5.25	5.40
SAMPLE 3	8.72	9.38	4.43	4.53	2.41	2.24	7.09	6.92	5.43	5.31
MEAN OF DIFFERENCE	0.35	0.31	0.15	0.19	0.06	0.15	0.11	0.17	0.07	0.04
MEAN OF REAL VALUES	8.65	9.31	4.45	4.41	2.34	2.25	7.09	7.03	5.33	5.36
ROTATION ASSEMBLY										
MEASURE NUMBER	1		2		3		4		5	
REFERENCE CAD (MM)	2.40		1.26		1.99		0.85		5.66	
PRINTED (MM)	GF 12	PA 12	GF 12	PA 12	GF 12	PA 12	GF 12	PA 12	GF 12	PA 12
SAMPLE 1	2.19	2.35	1.29	1.24	1.92	1.92	0.74	0.96	5.43	5.88
SAMPLE 2	2.50	2.29	1.21	1.23	1.94	1.91	0.92	0.82	5.41	5.92
SAMPLE 3	2.61	2.37	1.24	1.26	1.82	1.95	0.81	0.89	5.45	5.88
MEAN OF DIFFERENCE	0.03	0.06	0.01	0.02	0.10	0.06	0.03	0.04	0.23	0.23
MEAN OF REAL VALUES	2.43	2.34	1.25	1.24	1.89	1.93	0.82	0.89	5.43	5.89
AVERAGE TOTAL MEAN OF										
0.11										

Appendix H



IDENTIFIED CHALLENGES & CONCERNS
Brainstorming
CLUSTER V1 & BRAIN STORMING
CLUSTER V2 & BRAIN STORMING
Mind map
PRINT AND TEST
FRAMEWORK
OPPORTUNITIES AND FUTURE STEPS
FUTURE RESEARCH
Activities
JURNEY MAP
FRAMEWORK/ PRINTING ITERATION
SUPPORT TESTING
Opportunities
SECURE SUPPLY CHAIN
LOW RUN TEST
FULL SCALE
STAGE
OBJECTIVES

Procedural Checks - IDE Master Graduation

TU Delft

APPROVAL PROJECT BRIEF
To be filled in by the chair of the supervisory team.

chair [redacted] date [redacted] signature [redacted]

CHECK STUDY PROGRESS
To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: [redacted] EC

Of which, taking the conditional requirements into account, can be part of the exam programme [redacted] EC

List of electives obtained before the third semester without approval of the BoE

★ YES all 1st year master courses passed

NO missing 1st year master courses are:

name [redacted] date [redacted] signature [redacted]

FORMAL APPROVAL GRADUATION PROJECT
To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **.
Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: ★ APPROVED NOT APPROVED

Procedure: ★ APPROVED NOT APPROVED

comments

name [redacted] date [redacted] signature

Initials & Name [redacted] Student number [redacted]

Title of Project ADDITIVE MANUFACTURING FOR SPARE PARTS IN VACUUM CLEANERS

Personal Project Brief - IDE Master Graduation

TU Delft

ADDITIVE MANUFACTURING FOR SPARE PARTS IN VACUUM CLEANERS

project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 27 - 03 - 2023

08 - 09 - 2023 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

1.Context of the project:

Recent climate change issues and the European Parliament's measures to combat the environmental effect of home items have prompted businesses to seek more sustainable tactics. Several sustainability interventions are being investigated in order to reimagine how the design process might be reinvented in order to lower the footprint of manufacturing processes and the product life cycle.

Among these new strategies, there is a growing interest in the right to repair as a result of new legislation with the same name adopted by the European Parliament. Repairability encompasses a variety of tactics aimed at increasing product life cycles also including consumers in the process of repairing their own items. This approach intends to help users and businesses in a massively accessible repair system, from universal toolboxes to the provision of accessible replacement parts. In this context, 3D printing technology has opened up new possibilities for enterprises and people alike for self-repair, providing a cost-effective and time-efficient alternative for accessible spare parts.

Furthermore, this new in-house production approach has resulted in the formation of new user communities by designing accessories for items, therefore assisting in the extension of the life expectancy of home appliances.
3D printing has risen to prominence in recent years as a result of technological advancements, the freedom it provides throughout the design process, and the user's ability to make low-cost customized projects. By combining the benefits of 3D printing with other sustainability tactics like modularity and re-manufacturing, a new system of sustainable design for future products may be developed.

This case study is appropriate for Versuni's needs, as 3D printing technology may provide a new dimension to product design and circularity. An alternate technique to reducing reliance on manufacturing lines and the necessity for spare part storage, hence streamlining logistics for replacement parts to households. Additionally, this intervention can help bring outdated equipment back to life, making it a viable option for emerging economies.

2.Main stakeholders:

Versuni, for example, is adopting an active approach to investigating new measures and alternatives to its core business. As stated on their website and in their sustainability reports, they are operating in accordance with UN Sustainable Development Goals 12 and 13, guaranteeing sustainable consumption and production patterns and taking immediate action to address climate change and its consequences. This translates into incorporating Eco-design into their innovation processes and collaborating with sustainable suppliers to lessen the environmental impact of their activities. Exploration of sustainable techniques for their vacuum cleaner design aligns with their goal and vision, offering a strategic advantage to respond to the problem of their products' current and future repairability.

space available for images / figures on next page

Personal Project Brief - IDE Master Graduation

introduction (continued): space for images

image / figure 1: Example of 3D printed spar parts. (TU Delft SDE department research)

image / figure 2: 3D printing used to repair a Camera (ALL3DP)

Personal Project Brief - IDE Master Graduation

TU Delft

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

Repairability necessitates a system that ensures the quick availability of replacement parts, which implies that many components must be created and maintained on hand. 3D printing of spare parts can deliver a solution to these challenges thanks to its time efficiency and cost-effectiveness, bringing the repair solutions to a local scale. In order to assure the effective implementation of this methodology, the industry faces the
following challenges: 1 (Part fit requirements), 2 (Sustainability strategies intervention),3 (Simplifying Assemblies)
(1) 3D printing spare parts necessitate the use of CAD files that are created to meet the technical standards of theiroriginal counterparts. Original parts are often produced utilizing various procedures such as injection moulding.Because of this distinction, original files are frequently ineligible for 3D printing unless some adjustments are made. Asa result, a methodical strategy is needed to convert the original data into a format that meets the original performancecriteria. (2) Businesses that deploy a 3D printing solution must assure the quality of the produced replacement parts iflocal workshops are integrated into their system. This would necessitate more control over the 3D printing process, aswell as, as mentioned previously, ensuring that the CAD models meet the performance criteria of the original parts.This would provide a hurdle because 3D printing technology is still limited in some circumstances, as some needs arestill unattainable with this technology. Other solutions, such as re-manufacturing, would assist to fill in the holes in thesystem in these circumstances. (3) Repairability extends beyond the ability to replace a broken part. It is necessary tohave easy access to the most vital elements and to be able to switch them out. To ensure accessibility and quickmaintenance, a mapping of the lifespan of each part is required. Furthermore, replacing features such as screws withalternative solutions such as snap-fit pieces will minimize system complexity, allowing people to do these jobs withgreater confidence and efficacy.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

Design an OEM managed 3D printing for repair methodology that allows for mass production of parts and 3D printing of spare parts, such that part and product quality can be guaranteed by the OEM

The aim of this project is to design a solution for the intervention of a 3D-printed spare parts system in the case of Philips Vacuum Cleaner. In order to achieve this, the following points will be addressed:

1.Report of the findings in the design of a vacuum cleaner from the perspective of 3D printing repairability for Philips'future product lines. Including the framework to classify spare parts suitability for 3D printing

2.Delivery of a prototype that embodies the result from the research with the consequent CAD models andmanufacturing solutions.3.Insight into the opportunities for further sustainable strategies in the development of domestic electronics.

Initials & Name [redacted] Student number [redacted]

Title of Project ADDITIVE MANUFACTURING FOR SPARE PARTS IN VACUUM CLEANERS

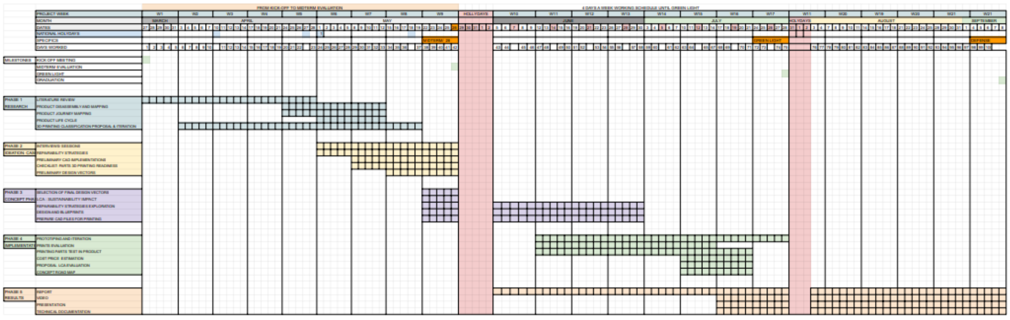
Personal Project Brief - IDE Master Graduation

TU Delft

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 27 - 3 - 2023 8 - 9 - 2023 end date



-Mid-term to Green light 4 day working schedule: Due to the requirement of traveling to the company headquarters in Drachten to continue the actual printing and testing of the prototype, the time accounted for traveling and setting in the new housings (Approximately 6.5 hours without housing time considered) will be considered by taking one day off each week from mid-term until the green light meeting. The hours of effort that cannot be committed to 3D printing and testing are thus compensated for by extending the Green light deadline by one week. This has no bearing on the total number of days and hours worked on the project. Being a total of 100 days.

Approach: For this project the three diamond method is selected.
1.Discovery:
-Literature review on AM technology, spare parts and repairability strategies.
2. Define:
-Evaluate current vacuum cleaner assembly and components.
-Product life cycle analysis.
-Framework for AM spare parts classification.
-AM printability of components evaluation.
3. Develop:
-Test and evaluate printed parts. Evaluate AM framework by redesigned vacuum cleaner components.
4. Deliver:

Initials & Name [redacted] Student number [redacted]

Title of Project ADDITIVE MANUFACTURING FOR SPARE PARTS IN VACUUM CLEANERS

Personal Project Brief - IDE Master Graduation

TU Delft

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

As an intern at FROLIC Design studio, I had the opportunity to be in an environment where sustainability and circularity solutions were prominent concerns. During this time, I worked on a studio research project in which, based on four different sustainability interviews, different concepts of home electronics were designed . During this experience, I realized the potential of such guidelines and strategies to benefit large corporations, such as Philips, regarding their environmental impact.

As a future product design engineer, I am conscious of the impact that my activity will have on the environment. Single plastic usage, lack of recyclability, greenwashing from big firms. I feel a responsibility of trying to explore other alternatives to the established system to achieve guidelines that would inspire future designers in the search for sustainable alternatives. I have been interested in user behavior and how design could make a difference in user awareness of the impact it has on the environment. This project implements The Right to Repair legislation and an universal repair toolkit for Philips products, making users more active in the circularity of a product.

With these concerns in mind, the Sustainable Design Engineering Lab at TU Delft was the perfect fit. I was interested in this division because of its extended experience in circularity and sustainability projects and by the number of professionals with a wide range of backgrounds and expertise.

It is in this assignment that I will love to fulfil the following personal ambitions:
-Understand the manufacturing process of established companies and their challenges when sifting to newalternatives for a more sustainable outcome.
-Deep dive into alternative materials.
-Gain a deeper understanding of circular design strategies and how they are implemented at a universal level byPhilips.
-Enhance my product development process while learning of new research methods and strengthening my designworkflow. As they say in FROLIC, ' If you have a process, you are less volatile".

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.