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## Design tools and methods for printed spare parts by manufacturers and consumers

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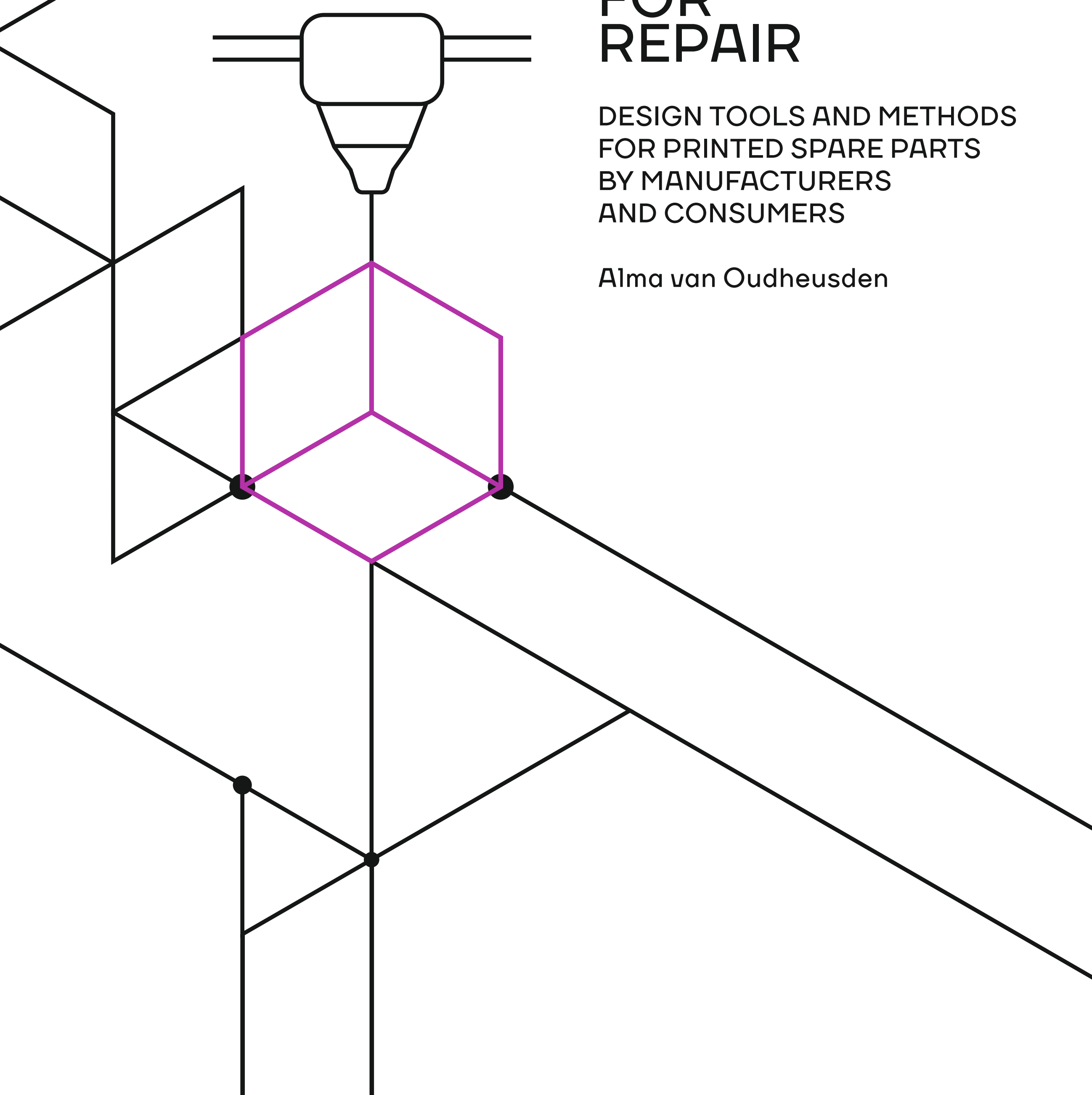
# 3D PRINTING FOR REPAIR

## DESIGN TOOLS AND METHODS FOR PRINTED SPARE PARTS BY MANUFACTURERS AND CONSUMERS

Alma van Oudheusden



# 3D printing for repair

## Design tools and methods for printed spare parts by manufacturers and consumers

## Dissertation

for the purpose of obtaining the degree of doctor at Delft University of Technology

by the authority of the Rector Magnificus Prof. dr. ir. T.H.J.J. van der Hagen;

Chair of the Board for Doctorates to be defended publicly on

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*All it took to unearth in the dust and the dirt*
*Some release or respite from the heat and the hurt*
*Was taking the time now and then to ask how I am*

— Joey Batey & Madeleine Hyland, *Battle Cries*

# CONTENTS

# SUMMARY

Throughout its evolution, our industrial economy has hardly moved beyond the linear consumption model of 'take-make-use-waste'. Alternative systems, such as the circular economy, are suggested to overcome the challenges of the linear economy. It proposes a restorative way of consumption where materials, products and parts are kept longer in use and no waste is generated. Repair helps to slow down the resource loops, with the added benefit that the required investments are lower than for other recovery options. However, spare parts may not be available when the production of the products ceases as it is difficult to predict how many spare parts are needed and storing them in warehouses can be costly. To make spare parts more generally available, they could be produced with additive manufacturing. Printed spare parts can be stored online instead of in a physical inventory, reducing delivery time, costs, emissions, and material waste. However, to fully optimise printed spare parts, a better understanding is needed of the design considerations that are involved.

In this dissertation, we explore how additive manufacturing can be used to produce plastic spare parts for the repair of consumer products. By reviewing the repairs of consumer products in repair café's, we estimate that around 8-29% of plastic spare parts are currently suitable for additive manufacturing. As most parts are currently unsuitable for additive manufacturing, the design of these printed spare parts needs to be aligned with the capabilities of the technology. This requires a better understanding of the specific design considerations. We need to find what design aspects are suitable for the use of additive manufacturing and which are more difficult. This will help us to determine the design complexity and what the biggest design challenges will be. Also, we investigate how to design parts that facilitate the use of additive manufacturing. Since parts can be designed by either the consumer or the manufacturer, it is important to distinguish between design in consumer self-repair and in manufacturer-enabled professional repair. These design perspectives are explicitly included in this dissertation.

Through our studies, we found that the suitability of a part is determined by the combination of part requirements, rather than a single complex requirement. A careful balance between design, material and manufacturing is needed before a spare part can be printed. Therefore, the design requirements should be considered in the context of their overall functionality. To support designers in their assessment of part suitability, we compared the capabilities of injection moulding and additive manufacturing for a wide range of requirements. By understanding the gap between the two manufacturing methods and adjusting the design accordingly, it becomes easier to produce 3D-printed spare parts.

While most plastic part designs are currently unsuitable for additive manufacturing, only small adjustments are generally required to ensure that a part design is suitable for both injection moulding and additive manufacturing. Most of the challenges for plastic printed spare parts can be addressed through careful design. For consumers, we constructed the 3D-printing for Repair process with instruction guide that provides a step-by-step approach to design a printed spare part for a broken or missing product part. For manufacturers, we developed the equivalent design process to help designers to develop solutions that are suitable for both injection moulding and additive manufacturing. However, if a product cannot be repaired at its part level, investing in the development of printed spare parts does not make sense. Therefore, designing for repair is a necessity for creating printed spare parts.

It is easier to enable 3D-printed spare parts early in the design, as both the part designs for injection moulding and additive manufacturing can still be modified. With the equivalent design process, designers can prioritise design solutions that work for both manufacturing methods. If printed spare parts are introduced later in the product lifecycle, the design process becomes less flexible as the designer needs to consider an already-existing product. This limits a designer to optimise design decisions or to explore novel working structures. While printed spare parts can still be used for existing products, more careful consideration of the design limitations is needed in that case. Also, the design of a printed spare part should focus on its intended function, rather than replicating its material or shape. This is especially important when redesigning or reverse-engineering existing parts. Most printed parts and materials will perform differently from the original parts and materials they replace. To facilitate the design of printed spare parts, designers should concentrate on creating parts that are functionally equivalent, rather than identical. Prioritising functional equivalence through the equivalent design process will reduce the design workload while providing considerable flexibility for design optimisation based on the respective manufacturing capabilities.

Additive manufacturing is a promising method for producing spare parts. While it may not be a systematic solution for all parts and products, it can provide spare parts long after initial production has ceased or extend the lifetime of legacy products. There is potential for further research and development to ensure printed spare parts are sustainable, viable and safe. More sustainable design methods can be integrated into the design of printed spare parts, and additive manufacturing methods can be developed further to enhance both their manufacturing capabilities and sustainability impact. However, as additive manufacturing is flexible and rapidly evolving, it could be the missing link to enable long-term product repairs in the future.

# SAMENVATTING

De ontwikkeling van onze industriële economie is nauwelijks verder gekomen dan het lineaire consumptiemodel van 'nemen-maken-gebruiken-afdanken'. Alternatieve systemen, zoals de circulaire economie, worden voorgesteld om de uitdagingen van de lineaire economie te overwinnen. In de circulaire economie worden materialen, producten en onderdelen langer gebruikt en wordt er nagenoeg geen afval geproduceerd. Het repareren van producten helpt in het behouden van grondstoffen, met als bijkomend voordeel dat de vereiste investeringen lager zijn dan voor andere verwerkingsmethodes. Het is echter mogelijk dat er geen reserveonderdelen meer op voorraad zijn nadat de productie van het product wordt stopgezet, aangezien het moeilijk te voorspellen is hoeveel reserveonderdelen er nodig zijn en de opslag ervan duur kan zijn. Om reserveonderdelen beter beschikbaar te maken zouden ze geproduceerd kunnen worden met additive manufacturing. Geprinte onderdelen kunnen online bewaard worden in plaats van in een fysiek warenhuis, waardoor de levertijd, kosten, uitstoot en materiaalverspilling afnemen. Voor het optimaliseren van deze geprinte onderdelen is echter meer inzicht nodig in welke overwegingen een rol spelen in het ontwerp ervan.

In dit proefschrift verkennen we welke additive manufacturing methodes er gebruikt kunnen worden in de productie van plastic onderdelen voor de reparatie van consumentenproducten. Door de reparaties van consumentenproducten in Repair cafe's te bestuderen, schatten we dat ongeveer 8-29% van de plastic reserveonderdelen momenteel geschikt zijn voor additive manufacturing. Aangezien de meeste onderdelen momenteel ongeschikt zijn om te printen, moet het ontwerp van geprinte reserveonderdelen beter afgestemd worden op de mogelijkheden van de productiemethode. Hiervoor is een beter begrip nodig van de specifieke ontwerpoverwegingen. We moeten uitzoeken welke ontwerpaspecten beter geschikt zijn voor additive manufacturing en welke meer uitdagend zijn. Dit geeft ons meer inzicht in de complexiteit van het ontwerpproces en wat de grootste ontwerpuitdagingen zullen zijn. Ook onderzoeken we hoe we het ontwerp van de onderdelen kunnen afstemmen op het gebruik van additive manufacturing. Aangezien geprinte onderdelen ontworpen kunnen worden door zowel de consument als de fabrikant, is het belangrijk om onderscheid te maken tussen ontwerp voor zelfreparatie door de consument en ontwerp voor professionele reparatie door de fabrikant. Deze ontwerpperspectieven zijn expliciet meegenomen in dit proefschrift.

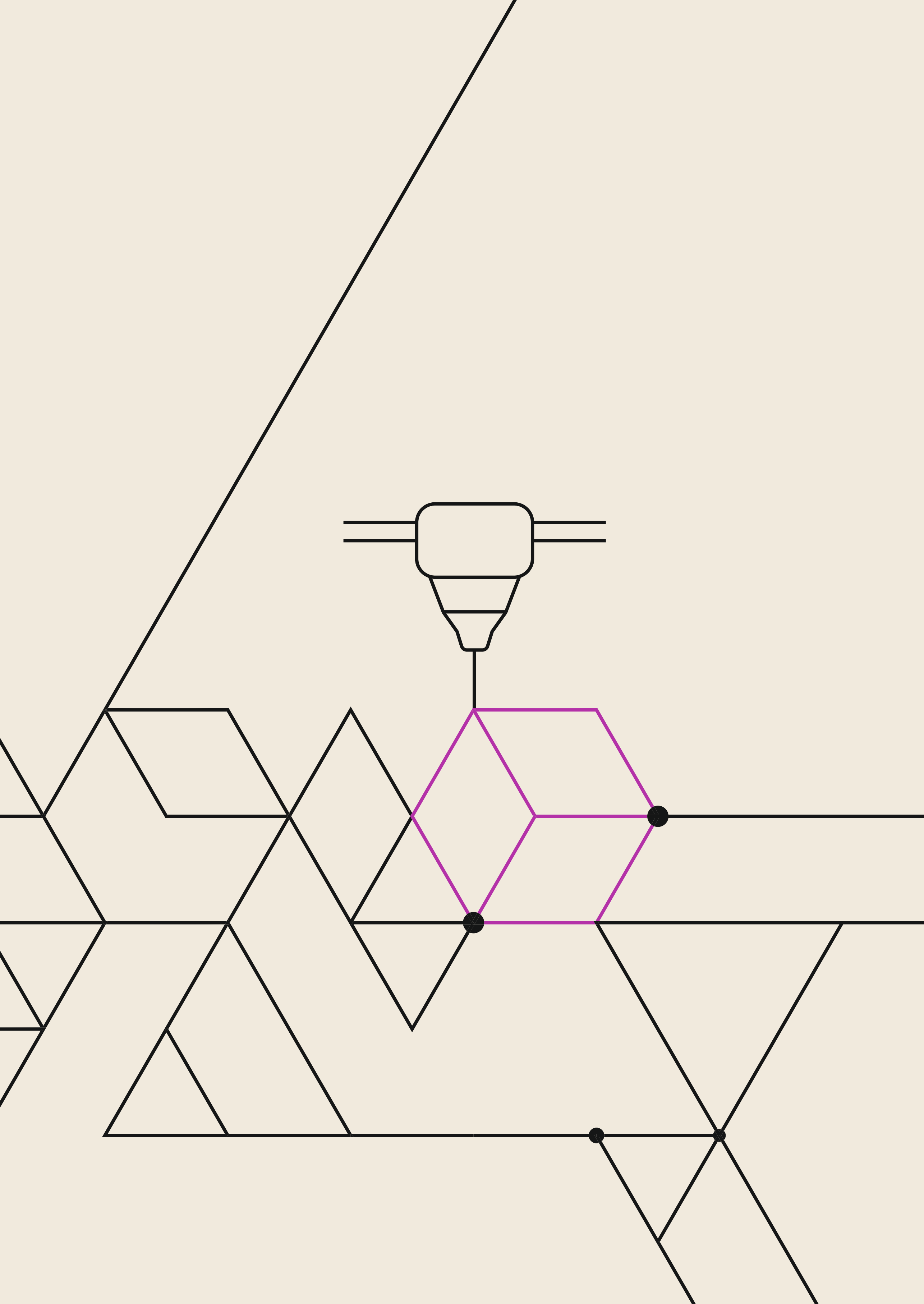
Uit onze onderzoeken bleek dat de geschiktheid van een onderdeel wordt bepaald door de manier waarin de ontwerpeisen gecombineerd zijn, in plaats van de complexiteit van een specifieke eis. Er is een zorgvuldige balans tussen ontwerp, materiaal en productie nodig voordat een onderdeel geprint kan worden. Hierdoor is het belangrijk om rekening te houden met de hoe de ontwerpeisen bijdragen aan de algehele functie van het onderdeel.

Om ontwerpers te ondersteunen bij hun beoordeling of een onderdeel geschikt is, hebben we een overzicht gemaakt waarin de mogelijkheden van spuitgieten en additive manufacturing vergeleken worden voor een groot aantal ontwerpeisen. Door de verschillen tussen de twee productiemethodes te begrijpen en het ontwerp hierop aan te passen, wordt het makkelijker om 3D-geprinte reserveonderdelen te produceren.

Hoewel het ontwerp van de meeste plastic onderdelen op dit moment ongeschikt is voor additive manufacturing, zijn er meestal maar kleine aanpassingen nodig om ervoor te zorgen dat het ontwerp van een onderdeel geschikt is voor zowel spuitgieten als additive manufacturing. De meeste uitdagingen voor geprinte reserveonderdelen van plastic kunnen worden aangepakt door een zorgvuldig ontwerp. Voor consumenten ontwikkelden we het 3D printing for Repair proces met instructiegids wat een duidelijke aanpak biedt om een geprint reserveonderdeel te ontwerpen voor een kapot of missend onderdeel in het te repareren product. Voor fabrikanten hebben we het equivalent design proces opgezet om ontwerpers te ondersteunen in het ontwikkelen van oplossingen die geschikt zijn voor zowel spuitgieten als additive manufacturing. Als een product echter niet op onderdeelniveau gerepareerd kan worden, heeft het geen zin om te investeren in de ontwikkeling van geprinte reserveonderdelen. Daarom is ontwerp voor reparatie noodzakelijk voor het maken van geprinte reserveonderdelen.

Het is makkelijker om 3D-geprinte reserveonderdelen vroeg in het ontwerp te realiseren aangezien het dan nog mogelijk is om de ontwerpen voor zowel spuitgieten als additive manufacturing aan te passen. Met het equivalent design proces kunnen ontwerpers prioriteit geven aan ontwerpoplossingen die werken voor beide productiemethodes. Als geprinte reserveonderdelen later in de levenscyclus van het product worden geïntroduceerd, wordt het ontwerpproces minder flexibel aangezien de ontwerper rekening moet houden met een al bestaand product. Dit beperkt een ontwerper in het optimaliseren van ontwerpbeslissingen of het verkennen van nieuwe werkstructuren. Hoewel geprinte onderdelen nog steeds kunnen worden gebruikt voor bestaande producten, moet er in dat geval meer rekening gehouden worden met de beperkingen van het ontwerp. Hierbij is het belangrijk dat het ontwerp van het geprinte onderdeel zich richt op de beoogde functie in plaats van op het nabootsen van het materiaal of de vorm. Dit is vooral belangrijk bij het herontwerpen of repliceren van bestaande onderdelen. De meeste geprinte onderdelen en materialen zullen anders presteren dan de originele onderdelen en materialen die ze vervangen. Om het ontwerpen van geprinte reserveonderdelen te vergemakkelijken, moeten ontwerpers zich richten op het maken van onderdelen die functioneel gelijkwaardig zijn, in plaats van identiek. Door deze functionele gelijkwaardigheid prioriteit te geven via het equivalent design proces, wordt de werklast van het ontwerpen verminderd terwijl er genoeg flexibiliteit geboden wordt voor het optimaliseren van het ontwerp op basis van de respectieve productiemogelijkheden.

Additive manufacturing is een veelbelovende methode voor het produceren van reserveonderdelen. Hoewel het misschien geen systematische oplossing is voor alle onderdelen en producten, kan het reserveonderdelen leveren lang nadat de initiële productie gestopt is en de levensduur van oude producten verlengen. Er is ruimte voor verder onderzoek en ontwikkeling om ervoor te zorgen dat geprinte reserveonderdelen duurzaam, haalbaar, en veilig zijn. Er kunnen meer duurzame ontwerpmethodes geïntegreerd worden in het ontwerpen van geprinte reserveonderdelen, en additive manufacturing methodes kunnen verder ontwikkeld worden om zowel hun productiemogelijkheden als duurzaamheidsimpact te verbeteren. Echter, aangezien additive manufacturing flexibel is en zich snel ontwikkelt, zou het de ontbrekende schakel kunnen zijn om productreparaties in de toekomst op lange termijn beschikbaar te maken.



CHAPTER 1

# Introduction

## 1.1 INTRODUCTION

Throughout its evolution, our industrial economy has hardly moved beyond the linear consumption model of 'take-make-use-waste'. Companies source materials, manufacture their products and sell these to consumers, who then dispose of them after use (Ellen MacArthur Foundation, 2013). This fast and linear consumption of products ultimately results in large amounts of valuable resources being lost to landfills, and large amounts of energy wasted in production and disposal (Dewberry et al., 2016). Keeping this linear system in use is expected to nearly double our resource use from 2011 to 2060, further increasing pressure on our global resources and the climate (Ellen MacArthur Foundation, 2021; IRP, 2019; OECD, 2019).

Alternative systems such as a circular economy are suggested to overcome the challenges of the linear economy (Ellen MacArthur Foundation, 2013; Ghisellini et al., 2016; Terzioğlu & Wever, 2021). The circular economy has the potential to offer meaningful solutions to waste and resource efficiency issues by narrowing and closing material loops (Bocken et al., 2016). It proposes a restorative way of consumption where materials, products and parts are kept longer in use and no waste is generated (Ellen MacArthur Foundation, 2013).

For the majority of products, it is environmentally desirable to extend the product lifetime (van Nes & Cramer, 2006). By extending the product lifetime, we can slow or reduce the flow of energy and materials and the related environmental degradation (Cooper, 1994; Stahel, 1986). One of the most common reasons for buying a new digital product is the breakdown of the old product (38%; Kantar, 2020), indicating that repair is an effective way to prolong the lifespan of a large share of products (Laitala et al., 2020). Repair helps to slow down the resource loops (Bocken et al., 2016), with the added benefit that the required investments are lower than for other recovery options (Scott & Weaver, 2014). To improve the consumers' right to repair, the European Commission has revised its eco-design measures to make repairs systematic, cost-efficient and attractive (Directive 2024/1799; European Commission, 2019). These measures currently include only a limited range of product groups, but additional regulations will extend this approach to a broader range of products (European Commission, 2024).

The upscaling of repair to become more effective in addressing waste still faces significant barriers (Svensson et al., 2018). Access to affordable and qualitative spare parts is one of the main challenges for the independent repair sector (van der Velden et al., 2023). These spare parts are normally held in stock by the manufacturer or third-party service provider to fulfil warranties. This means consumers can only repair their products for a short period of time and only through the service of the manufacturer (Hernandez & Miranda, 2020; Zhang et al., 2021). However, it is difficult to predict how many spare parts are needed, and storing them in warehouses can be costly (Odedairo, 2021; K. Yang & Niu, 2009). As a result, spare parts may not be available when the production of the products ceases (Zhang et al., 2021). To improve the availability of spare parts, the European eco-design regulations specify the minimum period in which spare parts should be available for certain products (Directive 2024/1799). For example, for washing machines, spare parts must be available within 15 days for at least 10 years after the last market release (Commission Regulation 2019/2023). This obligation to deliver spare parts for up to 10 year after sales increases the problem of stock keeping for manufacturers.

To make spare parts more generally available, they could be produced with additive manufacturing. Additive Manufacturing (AM), or 3D printing, includes a range of technologies that create parts by building them layer upon layer from virtual 3D models (Diegel et al., 2019). As such, printed spare parts can be stored online instead of in a physical inventory (Pérès & Noyes, 2006; Zanoni et al., 2019). This can reduce delivery time, costs, emissions, and material waste (Attaran, 2017; Chekurov et al., 2018). Additionally, AM-enabled supply chains allow local or in-situ production, which can reduce the need for additional transportation of the part (Holmström & Gutowski, 2017). While printed spare parts could be used throughout the product, it makes the most sense for product-specific parts. Standardised parts, such as screws, bolts, and springs, are already mass-produced and readily available. Additionally, these parts are often difficult or near-impossible to reproduce with additive manufacturing. Product-specific parts, however, can only be used within their specific products. This means they are not readily in stock from standardised production. These parts are mostly plastic parts made with injection moulding, which could potentially be made with additive manufacturing. As injection moulding is unsuitable for on-demand manufacturing (Karania & Kazmer, 2007), these plastic parts would benefit the most from printed spare parts.

The question remains who should develop these printed spare parts, the consumer or the manufacturer? The emergence of additive manufacturing allows consumers to control the design and production of parts (Chekurov et al., 2018). This enables them to upgrade and repair products, even if this was not considered in the original design (Sauerwein et al., 2019). However, careful design adaptation and validation are required to ensure that the parts meet the quality standards of the manufacturer (Despeisse et al., 2017; González-Varona et al., 2020). Other important considerations include legislation, liability, and intellectual property rights of printed parts (Zijm et al., 2019). Another option is that the manufacturer drives the development of printed spare parts. This allows manufacturers to create spare parts that are specifically designed for additive manufacturing, which is more desirable than creating an exact copy of the original part (Brans, 2013). To fully optimise printed spare parts, the design modifications for additive manufacturing need to be considered in the initial product design (Salmi & Pei, 2023).

## 1.2 STATE OF THE ART AND RESEARCH GAPS

Broadly speaking, we distinguish two types of repair: self-repair and professional repair. Self-repair involves consumers repairing products themselves, aided by online resources such as YouTube or iFixit (Dewberry et al., 2016). This repair is facilitated by social communities such as Repair Cafes, which provide increased access to repair expertise, further reducing the effort and costs associated with repair (Bekin et al., 2007; Scott & Weaver, 2014). Professional repair is conducted by the manufacturer's repair network or independent repairers (Svensson et al., 2018). The manufacturer repair network consists of authorized repair shops, or less commonly, the repair department of the manufacturer itself (Lloveras et al., 2024). When authorized, repair shops follow the manufacturer's regulations and use licensed parts (Svensson et al., 2018). The professional repair by independent repairers shows similarities to both self-repair and authorized repair. These independent repairers need to balance a need for supplies and economic viability with competitiveness and profitability (Svensson-Hoglund et al., 2021). Due to these similarities, this repair approach is not considered separately in this dissertation. Whether a consumer chooses self-repair or professional repair depends on various factors such as the warranty period, feasibility, repair cost, and personal preferences (Svensson-Hoglund et al., 2021).

When and how a printed spare part is designed, depends on whether this is part of consumer self-repair or manufacturer-enabled professional repair. These perspectives are referred to as the consumer design perspective and manufacturer design perspective, respectively. Both of these design perspectives have a different approach to the design process, as shown in Figure 1.1. In consumer design, the printed spare part is designed by consumers as part of the product repair. This allows consumers to produce the missing spare parts after the initial production of the product has ceased (Zijm et al., 2019). In manufacturer design, the printed spare part is designed by the original designer as part of the original product design. This means the part design can be optimised or adapted to a specific printing method (Diegel et al., 2019). Also, compared to the consumer perspective, there is a wider range of printing methods and materials (Eyers & Potter, 2017). By investigating both perspectives, we can gain more insight into the possibilities and limitations of printed spare parts.

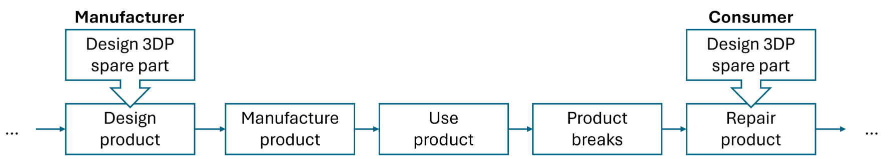



**Figure 1.1.** Product lifecycle with indications of in which phase the printed spare part is designed for the different research perspectives.

While consumer interest in repair is increasing (Scott & Weaver, 2014), there are still barriers that discourage consumers from repairing broken products (Pérez-Belis et al., 2017). Most importantly, a product must be technically repairable, meaning the product must be designed for repair (Roskladka et al., 2022, 2023). However, poor design such as problematic closures, glues, and welding leads to disassembly problems (Cooper & Salvia, 2018). A repairer must also have sufficient skills to repair a product successfully. Issues here include a lack of repair know-how and missing technical information about the product and its spare parts (Dewberry et al., 2017). Legislation such as patent and copyright laws can hinder access to the required tools or spare parts, especially for self-repair or unlicensed repair (Svensson et al., 2018). And finally, a consumer must be willing to repair the product. This decision is based on various factors, including the repair cost, initial price of the product, and convenience of repair (Scott & Weaver, 2014).

In the manufacturing industry, additive manufacturing is increasingly used to replace end-use parts (Salmi & Pei, 2023). This approach is mainly used to replace parts where the original replacement parts are unavailable or difficult to come by, such as in off-shore or military industries (Pérès & Noyes, 2006). Exemplary case studies include replacing a legacy diesel engine cylinder head (ExOne, 2025) or the production of obsolete ship parts (Ratcliffe, 2020). Besides replacement parts, additive manufacturing is commonly used for its unique capabilities such as geometrical freedom. Notable examples here include the production of lightweight structures for aerospace or automotive industries (Zijm et al., 2019), such as ducting parts for Bell helicopters (Stratasys, 2019). The specific properties of printed parts depend on the type of additive manufacturing. The most common methods are material extrusion, powder bed fusion, and vat polymerisation, which typically provide the highest part quality (Salmi & Pei, 2023).

In consumer products, printed spare parts are more uncommon. Some companies use additive manufacturing to produce spare parts for consumer products, such as Whirlpool (Spare Parts 3D, 2021) and Tefal (2022, 2025), although no specific parts are mentioned. Alternatively, there are cases where consumers create the required spare parts themselves and share the digital files via online platforms such as Thingiverse or MyMiniFactory (Lorenzen & Paape, 2018). More often, additive manufacturing is used in consumer products to create unique, customized parts with better reparability or upgradability, as well as to take advantage of small-scale production benefits. Examples here include bespoke luminaires (Signify, 2025), the plastic parts on the Original Prusa i3 3D printers (Prusa Research, 2025), and 3D-printed headsets from print+ (2025) and head(amame) (2025). Most of these brands, except for Signify, also allow consumers to print the (spare) parts themselves or through third-party printing providers.

In most cases, the use of additive manufacturing for the production of spare parts was not originally intended in the design of the product (Sauerwein et al., 2019). The design of the part is optimized for the original mass-production method, which is often significantly different from additive manufacturing (Salmi & Pei, 2023). It is complex to adapt the existing part design for additive manufacturing due to the interdependence between design, process and material selection (Despeisse et al., 2017). As a result, a large number of parts will only be feasible for additive manufacturing after significant (re)design efforts (Frandsen et al., 2020; Holmström & Gutowski, 2017). This could include optimizing the geometry or adjusting the material (Chaudhuri et al., 2020; Westerweel et al., 2018). However, it is difficult to generalize design rules for additive manufacturing over different products and printing methods (Westerweel et al., 2018; L. Yang et al., 2017). Considerable skill is required to determine how part function and geometry are linked, so the question is how we can support the design process (Ganter et al., 2021). There are numerous design frameworks on additive manufacturing (Haruna & Jiang, 2020; Leary, 2020; Vaneker et al., 2020; Wiberg et al., 2019), but these have not been created with spare parts in mind. Instead, we need a new design approach that bridges the differences between the two manufacturing methods.

## 1.3 RESEARCH AIM

In this dissertation, we explore how additive manufacturing can be used to produce plastic spare parts for the repair of consumer products. As most parts are currently unsuitable for additive manufacturing, the design of these printed spare parts needs to be aligned with the capabilities of the technology. This requires a better understanding of the design considerations that are involved. We need to find what design aspects are suitable for the use of additive manufacturing and which are more difficult. This will help us to determine the design complexity and what the biggest design challenges will be. Also, we investigate how to design parts that facilitate the use of additive manufacturing. Since parts can be designed by either the consumer or the manufacturer, it is important to distinguish between design in consumer self-repair and in manufacturer-enabled professional repair. These design perspectives were explicitly included in our research. For example, we introduce the 3D-printing for Repair (3DPfR) process, which is focused on consumers. By identifying the possibilities and limitations of additive manufacturing compared to conventional manufacturing and adjusting the design accordingly, we can determine how spare parts can be produced with additive manufacturing. This led us to the following two main research questions for this dissertation:

**RQ1.** What design aspects of plastic spare parts in consumer products determine whether or not they are suitable for additive manufacturing?

**RQ2.** How should we design plastic parts to make them more suitable for additive manufacturing of spare parts?

Main research question 1 is addressed in Chapter 2, Chapter 4 and Chapter 5, where the following sub-questions are answered:

**RQ1.1.** How can we evaluate the printability of product parts based on part requirements? (Chapter 4)

**RQ1.2.** What repairs within repair communities can be met through 3D-printing spare parts? (Chapter 2)

**RQ1.3.** Which design requirements drive the design for both injection moulding and additive manufacturing? (Chapter 5)

Main research question 2 is addressed in Chapter 3, Chapter 5 and Chapter 6, where the following sub-questions are answered:

**RQ2.1.** How can the 3DPfR process that leads to a successful repair be described? (Chapter 3)

**RQ2.2.** What is the influence of previous experience, process implementation, and part complexity on the overall success of the 3DPfR process? (Chapter 3)

**RQ2.3.** How can these design requirements be used to facilitate the design of 3D-printed spare parts? (Chapter 5)

**RQ2.4.** How can a designer enable in the early stages of the design process that the injection-moulded original part and 3D-printed spare parts will be functionally equivalent? (Chapter 6)

Table 1.1 shows how the sub-questions relate to the main questions and consumer and manufacturer design perspectives.

**Table 1.1.** The sub-questions of each chapter in relation to the main research questions and design perspectives.

| | Consumer perspective | Manufacturer perspective |
|---|---|---|
| **RQ1. Suitable aspects for additive manufacturing** | RQ1.1. How can we evaluate the printability of product parts based on part requirements? (Chapter 4) | |
| | RQ1.2. What repairs within repair communities can be met through 3D-printing spare parts? (Chapter 2) | RQ1.3. Which design requirements drive the design for both injection moulding and additive manufacturing? (Chapter 5) |
| **RQ2. Designing printed spare parts** | RQ2.1. How can the 3DPfR process that leads to a successful repair be described? (Chapter 3) | RQ2.3. How can these design requirements be used to facilitate the design of 3D-printed spare parts? (Chapter 5) |
| | RQ2.2. What is the influence of previous experience, process implementation, and part complexity on the overall success of the 3DPfR process? (Chapter 3) | RQ2.4. How can a designer enable in the early stages of the design process that the injection-moulded original part and 3D-printed spare parts will be functionally equivalent? (Chapter 6) |

## 1.4 RESEARCH OUTLINE

To investigate the relation between design and part printability, we used both qualitative and quantitative studies. Overall, a mixed-method approach was used, based on literature review and case studies. Below is a summary of the research approach for each sub-question.

**Chapter 2** described an initial exploration of the demand for printed spare parts in repair communities, and what product and repair types would be the most suitable for such parts. To find what repairs in repair communities can be met through 3D-printing spare parts (RQ1.2), we counted the most common products brought in for repair and coded whether these repairs would be solvable with printed spare parts.

These insights are used in **Chapter 3** to establish a framework on how to integrate printed spare parts into consumer self-repair and to find what process factors are relevant for a successful repair. To find how the 3DPfR process that leads to a successful repair can be described (RQ2.1), we performed a literature review and experimental case study to find the most common process steps. To find the influence of previous experience, process implementation, and part complexity on the overall success of the 3DPfR process, we collected data during a practicum where participants ran through one iteration of the process.

**Chapter 4** applies the framework and findings to a case study and makes a first exploration of what design requirements can be used to predict the suitability of product parts for additive manufacturing. To find how we can evaluate the printability of product parts based on part requirements (RQ1.1), we constructed a list of part requirements and performed a theoretical assessment of all the parts in a vacuum cleaner. This assessment was validated through printing and testing some of these parts.

This list of design requirements is further refined in **Chapter 5**, which also compares the manufacturing capabilities of injection moulding and additive manufacturing on an industrial level. To find which design requirements drive the design for both injection moulding and additive manufacturing (RQ1.3), we used literature review to identify which design requirements are relevant and to assess the capabilities of injection moulding and additive manufacturing for these requirements. To find how these design requirements can be used to facilitate the design of 3D-printed spare parts (RQ2.3), we performed an illustrative case to show how the results can indicate the suitability of a part for additive manufacturing.

**Chapter 6** uses the insights of the previous chapters to construct a new design approach for manufacturers to enable the use of printed spare parts in the original design of the part. To find how a designer can ensure early in the design process that the injection-moulded original part and 3D-printed spare parts will be functionally equivalent (RQ2.4), we combined insights from literature and previous research to explore what a possible design process could look like. We linked our results to earlier insights to create two tools to support the design process and performed two case examples to illustrate and evaluate the results.

Finally, **Chapter 7** discusses the findings and conclusions of this research.

This dissertation is founded on a series of scientific publications. The footnote at the beginning of each chapter mentions the original reference, including all the authors that were involved. To adapt the publications into the chapters of this dissertation, the layout, chapter numbers, and section numbers have been adjusted, and some of the reference styles and headings have been changed for consistency. No changes have been made to the contents of each chapter. In Chapter 2, I made a comparable contribution to research and writing as the first author. For Chapters 3-6, I was the main author and researcher. This meant I was responsible for most of the research, including conceptualisation, data collection and curation, and writing and editing the main body of text.

## 1.5 REFERENCES

Attaran, M. (2017). The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing. *Business Horizons*, *60*(5), 677–688. https://doi.org/10.1016/j.bushor.2017.05.011

Bekin, C., Carrigan, M., & Szmigin, I. (2007). Beyond recycling: 'commons-friendly' waste reduction at new consumption communities. *Journal of Consumer Behaviour*, *6*(5), 271–286. https://doi.org/10.1002/cb.221

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

Brans, K. (2013). 3D Printing, a Maturing Technology. *IFAC Proceedings Volumes*, *46*(7), 468–472. https://doi.org/https://doi.org/10.3182/20130522-3-BR-4036.00112

Chaudhuri, A., Gerlich, H. A., Jayaram, J., Ghadge, A., Shack, J., Brix, B. H., Hoffbeck, L. H., & Ulriksen, N. (2020). Selecting spare parts suitable for additive manufacturing: a design science approach. *Production Planning and Control*, *32*(8), 670–687. https://doi.org/10.1080/09537287.2020.1751890

Chekurov, S., Metsä-Kortelainen, S., Salmi, M., Roda, I., & Jussila, A. (2018). The perceived value of additively manufactured digital spare parts in industry: An empirical investigation. *International Journal of Production Economics*, *205*(September), 87–97. https://doi.org/10.1016/j.ijpe.2018.09.008

Cooper, T., & Salvia, G. (2018). Fix it: Barriers to Repair and Opportunities for Change. In R. Crocker & K. Chiveralls (Eds.), *Subverting Consumerism: Reuse in an Accelerated World* (pp. 147–165). Routledge.

Despeisse, M., Baumers, M., Brown, P., Charnley, F., Ford, S. J., Garmulewicz, A., Knowles, S., Minshall, T. H. W., Mortara, L., Reed-Tsochas, F. P., & Rowley, J. (2017). Unlocking value for a circular economy through 3D printing: A research agenda. *Technological Forecasting and Social Change*, *115*, 75–84. https://doi.org/10.1016/j.techfore.2016.09.021

Dewberry, E. L., Saca, L., Moreno, M., Sheldrick, L., Sinclair, M., Makatsoris, C., & Charter, M. (2016). A landscape of repair. *Proceedings of the Sustainable Innovation 2016. Circular Economy Innovation and Design.*, 76–85. https://cfsd.org.uk/events/sustainable-innovation-2016/

Dewberry, E. L., Sheldrick, L., Sinclair, M., Moreno, M., & Makatsoris, C. (2017). Developing scenarios for product longevity and sufficiency. In C. Bakker & R. Mugge (Eds.), *PLATE: Product Lifetimes And The Environment* (pp. 108–113). Delft University of Technology and IOS Press. https://doi.org/10.3233/978-1-61499-820-4-108

Diegel, O., Nordin, A., & Motte, D. (2019). *Additive Manufacturing Technologies BT - A Practical Guide to Design for Additive Manufacturing*. Springer Nature Singapore Pte Ltd. https://doi.org/10.1007/978-981-13-8281-9_2

Directive 2024/1799. (2024). *Directive (EU) 2024/1799 of the European Parliament and of the Council of 13 June 2024 on common rules promoting the repair of goods and amending Regulation (EU) 2017/2394 and Directives (EU) 2019/771 and (EU) 2020/1828Text with EEA relevance.* http://data.europa.eu/eli/dir/2024/1799/oj

Ellen MacArthur Foundation. (2013). *TOWARDS THE CIRCULAR ECONOMY Economic and business rationale for an accelerated transition*.

Ellen MacArthur Foundation. (2021). *Universal Circular Economy Policy Goals*.

European Commission. (2019). *The new ecodesign measures explained*. https://ec.europa.eu/commission/presscorner/detail/en/qanda_19_5889

European Commission. (2024). *Sustainable products to become norm for consumers as new law enters into force*. https://environment.ec.europa.eu/news/sustainable-products-be-norm-consumers-new-regulation-2024-07-19_en

ExOne. (2025). *Obsolete Replacement Part Delivered in Two Weeks with Digital Casting*. https://www.exone.com/en-US/Speed-3D-Mold-Case-Study

Eyers, D. R., & Potter, A. T. (2017). Industrial Additive Manufacturing: A manufacturing systems perspective. *Computers in Industry*, *92–93*, 208–218. https://doi.org/10.1016/j.compind.2017.08.002

Frandsen, C. S., Nielsen, M. M., Chaudhuri, A., Jayaram, J., & Govindan, K. (2020). In search for classification and selection of spare parts suitable for additive manufacturing: a literature review. *International Journal of Production Research*, *58*(4), 970–996. https://doi.org/10.1080/00207543.2019.1605226

Ganter, N. V., Bode, B., Gembarski, P. C., & Lachmayer, R. (2021). Method for Upgrading a Component Within Refurbishment. *Proceedings of the Design Society*, *1*(August), 2057–2066. https://doi.org/10.1017/pds.2021.467

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

González-Varona, J. M., Poza, D., Acebes, F., Villafáñez, F., Pajares, J., & López-Paredes, A. (2020). New business models for sustainable spare parts logistics: A case study. *Sustainability (Switzerland)*, *12*(8), 3071. https://doi.org/10.3390/SU12083071

Haruna, A., & Jiang, P. (2020). A Design for Additive Manufacturing Framework: Product Function Integration and Structure Simplification. *IFAC-PapersOnLine*, *53*(5), 77–82. https://doi.org/10.1016/j.ifacol.2021.04.127

head(amame). (2025). *About Us*. https://headamame.com/pages/about-us

Hernandez, R. J., & Miranda, C. (2020). *Empowering Sustainable Consumption by Giving Back to Consumers the 'Right to Repair.'* 1–15.

Holmström, J., & Gutowski, T. (2017). Additive Manufacturing in Operations and Supply Chain Management: No Sustainability Benefit or Virtuous Knock-On Opportunities? *Journal of Industrial Ecology*, *21*, S21–S24. https://doi.org/10.1111/jiec.12580

IRP. (2019). *Global Resources Outlook 2019: Natural Resources for the Future We Want*. United Nations Programme.

Karania, R., & Kazmer, D. (2007). Low Volume Plastics Manufacturing Strategies. *Journal of Mechanical Design*, *129*(12), 1225–1233. https://doi.org/10.1115/1.2790978

Laitala, K., Klepp, I. G., Haugrønning, V., Throne-Holst, H., & Strandbakken, P. (2020). Increasing repair of household appliances, mobile phones and clothing: Experiences from consumers and the repair industry. *Journal of Cleaner Production*, *282*, 125349. https://doi.org/10.1016/j.jclepro.2020.125349

Leary, M. (2020). Digital design for AM. In *Design for Additive Manufacturing*. https://doi.org/10.1016/b978-0-12-816721-2.00003-8

Lloveras, J., Pansera, M., & Smith, A. (2024). On 'the Politics of Repair Beyond Repair': Radical Democracy and the Right to Repair Movement. *Journal of Business Ethics*. https://doi.org/10.1007/s10551-024-05705-z

Lorenzen, A., & Paape, A. (2018). *Leitfaden für den Einsatz 3D-gedruckter Ersatzteile in der Reparatur*. https://3d-reparatur.de/materialien-und-downloads/#broschuere

Odedairo, B. O. (2021). Managing Spare Parts Inventory by Incorporating Holding Costs and Storage Constraints. *Journal of Engineering, Project, and Production Management*, *11*(2), 139–144. https://doi.org/10.2478/jeppm-2021-0014

OECD. (2019). *Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences*. OECD Publishing. https://doi.org/https://doi.org/10.1787/9789264307452-en

Pérès, F., & Noyes, D. (2006). Envisioning e-logistics developments: Making spare parts in situ and on demand. State of the art and guidelines for future developments. *Computers in Industry*, *57*(6), 490–503. https://doi.org/10.1016/j.compind.2006.02.010

Pérez-Belis, V., Braulio-Gonzalo, M., Juan, P., & Bovea, M. D. (2017). Consumer attitude towards the repair and the second-hand purchase of small household electrical and electronic equipment. A Spanish case study. *Journal of Cleaner Production*, *158*, 261–275. https://doi.org/10.1016/j.jclepro.2017.04.143

print+. (2025). *Our vision*. https://www.print.plus/our-vision

Prusa Research. (2025). *About us*. https://www.prusa3d.com/page/about-us_77/

Ratcliffe, S. (2020). *3D-printed spare parts revolutionize maritime supply chain*. https://www.dnv.com/expert-story/maritime-impact/3D-printed-spare-parts-revolutionize-maritime-supply-chain/

Roskladka, N., Jaegler, A., & Miragliotta, G. (2023). From "right to repair" to "willingness to repair": Exploring consumer's perspective to product lifecycle extension. *Journal of Cleaner Production*, *432*. https://doi.org/10.1016/j.jclepro.2023.139705

Roskladka, N., Miragliotta, G., Bressanelli, G., & Saccani, N. (2022). *Exploiting the Right to Repair towards a sustainable future: a systematic literature review*.

Salmi, M., & Pei, E. (2023). Additive manufacturing processes and materials for spare parts. *Journal of Mechanical Science and Technology*, *37*(11), 5979–5990. https://doi.org/10.1007/s12206-023-1034-0

Sauerwein, M., Doubrovski, E., Balkenende, R., & Bakker, C. (2019). Exploring the potential of additive manufacturing for product design in a circular economy. *Journal of Cleaner Production*, *226*, 1138–1149. https://doi.org/10.1016/j.jclepro.2019.04.108

Scott, K. A., & Weaver, S. T. (2014). To Repair or Not to Repair: What is the Motivation? *Journal of Research for Consumers*, *January 2014*, 1–31.

Signify. (2025). *3D printing by Signify*. https://www.signify.com/global/innovation/3d-printing

Spare Parts 3D. (2021). *Spare Parts 3D joins up with Whirlpool on a 3D printing project*. https://spare-parts-3d.com/2021/11/24/whirlpool-spare-parts-3d-printing-project/

Stratasys. (2019). *Developing Flight-Ready Production Hardware with Laser Sintering*. https://www.stratasys.com/en/stratasysdirect/resources/case-studies/selective-laser-sintered-ecs-ducts-bell-helicopter/

Svensson, S., Richter, J. L., Maitre-ekern, E., Pihlajarinne, T., Maigret, A., & Dalhammar, C. (2018). The emerging 'Right To Repair ' Legislation in the EU and the USA. In *Going Green CARE INNOVATION 2018*.

Svensson-Hoglund, S., Richter, J. L., Maitre-Ekern, E., Russell, J. D., Pihlajarinne, T., & Dalhammar, C. (2021). Barriers, enablers and market governance: A review of the policy landscape for repair of consumer electronics in the EU and the U.S. *Journal of Cleaner Production*, *288*. https://doi.org/10.1016/j.jclepro.2020.125488

Tefal. (2022). *3D printen van onderdelen door Tefal* [Video recording]. YouTube. https://www.youtube.com/watch?v=GEq_DBSJz1c&t=4s&ab_channel=Tefal

Tefal. (2025). *Tefal is committed to repairability*. https://www.tefal.com.eg/en/repairability-page

Terzioğlu, N., & Wever, R. (2021). Integrating repair into product design education: Insights on repair, design and sustainability. *Sustainability (Switzerland)*, *13*(18). https://doi.org/10.3390/su131810067

van der Velden, M., Maitre-Ekern, E., & Wanja, D. K. (2023). The Role of Independent Repair in a Circular and Regenerative Economy. *Circular Economy and Sustainability*. https://doi.org/10.1007/s43615-023-00304-y

Vaneker, T., Bernard, A., Moroni, G., Gibson, I., & Zhang, Y. (2020). Design for additive manufacturing: Framework and methodology. *CIRP Annals*, *69*(2), 578–599. https://doi.org/10.1016/j.cirp.2020.05.006

Westerweel, B., Basten, R. J. I., & van Houtum, G. J. (2018). Traditional or Additive Manufacturing? Assessing Component Design Options through Lifecycle Cost Analysis. *European Journal of Operational Research*, *270*(2), 570–585. https://doi.org/10.1016/j.ejor.2018.04.015

Wiberg, A., Persson, J., & Ölvander, J. (2019). Design for additive manufacturing – a review of available design methods and software. *Rapid Prototyping Journal*, *25*(6), 1080–1094. https://doi.org/10.1108/RPJ-10-2018-0262

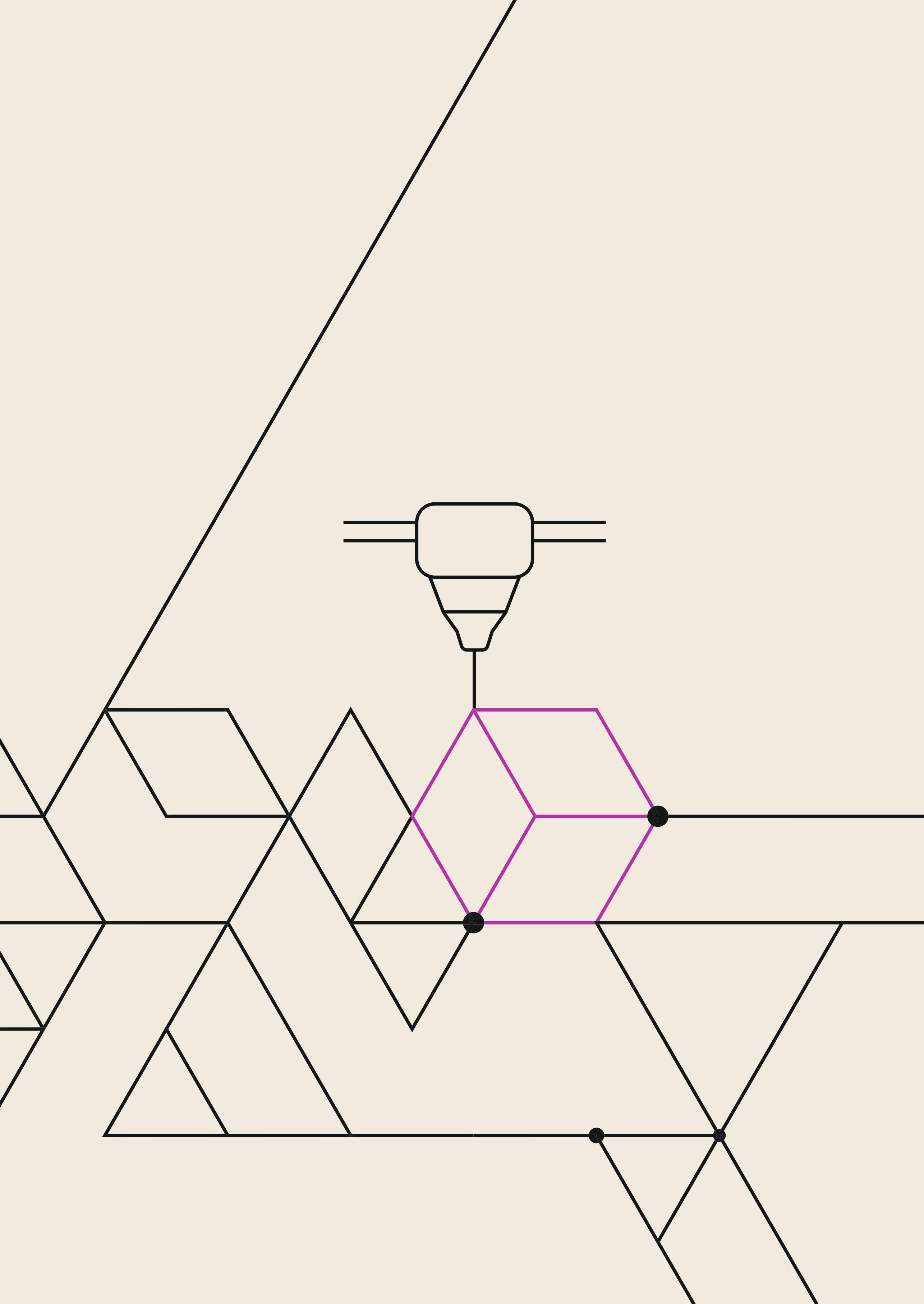
Yang, K., & Niu, X. (2009). Research on the spare parts inventory. *2009 16th International Conference on Industrial Engineering and Engineering Management*, 1018–1021. https://doi.org/10.1109/ICIEEM.2009.5344253

Yang, L., Hsu, K., Baughman, B., Godfrey, D., Francisco Medina, M. M., & Wiener, S. (2017). Design for additive manufacturing. In *Additive Manufacturing of Metals: The Technology, Materials, Design and Production* (1st ed., pp. 81–160). Springer International Publishing AG. https://doi.org/https://doi-org.tudelft.idm.oclc.org/10.1007/978-3-319-55128-9

Zanoni, S., Ashourpour, M., Bacchetti, A., Zanardini, M., & Perona, M. (2019). Supply chain implications of additive manufacturing: a holistic synopsis through a collection of case studies. *International Journal of Advanced Manufacturing Technology*, *102*(9–12), 3325–3340. https://doi.org/10.1007/s00170-019-03430-w

Zhang, S., Huang, K., & Yuan, Y. (2021). Spare parts inventory management: A literature review. *Sustainability (Switzerland)*, *13*(5), 1–23. https://doi.org/10.3390/su13052460

Zijm, H., Knofius, N., & van der Heijden, M. (2019). Additive Manufacturing and Its Impact on the Supply Chain. In *Operations, Logistics and Supply Chain Management* (pp. 521–543). https://doi.org/10.1007/978-3-319-92447-2_23



CHAPTER 2

# Opportunities For 3D-printable Spare Parts: Estimations From Historical Data

This chapter was originally published as Samenjo, K.; van Oudheusden, A.; Bolaños, J.; Flipsen, B.; Faludi, J. Opportunities For 3D-Printable Spare Parts: Estimations From Historical Data. In Proceedings of the 4th PLATE Virtual Conference, Limerick, Ireland, 26–28 May 2021.

## ABSTRACT

The Sharepair project aims to decrease the waste of electronic and electric consumer products and increase their useful life, by supporting repair communities and scaling up citizen repairs through digital tools. One of the focus areas of this project is to support the discovery or manufacturing of spare parts. With a 3D CAD model of a part and a 3D printer, repair communities could manufacture spare parts. This paper discusses the possibilities of identifying repairs, within repair communities, that can be met through 3D printed spare parts. To understand and identify these possibilities, the repair entries expressed in the Open Repair Database (ORD) from the Open Repair Alliance were examined. The analysis aimed to identify documented examples of repairs that have broken or missing parts, and estimate how many may be suitable for replacement by 3D printed versions. The ORD includes 41,874 repair data entries from 229 repair communities (Repair Café, Restart Project, Fixit Clinic, and Anstiftung) in eighteen countries. Repair entries include information such as product category, brand, model, repair status and notes regarding the repair process and result, all in different languages.

The analysis identified a list of the most commonly repaired product categories, brands, and models, as well as an estimate that between 7.5% and 29% of products in repair cafes that are not repaired today could be repaired with 3D printed spare parts. The analysis also showed that the data and information about the repairs is inconsistent, open to interpretation and often too limited to precisely pinpoint opportunities for 3D printed spare parts. Specifying the product parts that need repair or replacement and their functional requirements would be key to a successful identification. Thus, the study proposes recommendations to improve the process of capturing repair information that specifies the repair needs that can be met by the use of 3D printing.

## 2.1 INTRODUCTION

The Sharepair project aims to decrease the waste of electronic and electric equipment (WEEE) and to increase their useful life, by supporting repair communities and scaling up citizen repairs through digital tools. WEEE is a rapidly growing waste stream, partly because advances in technology have contributed to shorter product lifetimes (Cole, Cooper & Gnanapragasam, 2017). The most logical approach to closing the loop on product use and extending the product's life is simply to repair the product. However, while the concept of repair seems simple, it is seldom practiced (King et al., 2006). Consumer interest in repair is increasing (Scott & Weaver, 2014), but there are still barriers that discourage consumers from repairing broken products (Pérez-Belis et al., 2017). In a survey among self-repairers, Sabbaghi et al. (2016) found the main reasons for an unsuccessful product repair were the complicated repair process (26%), expensive spare parts (17%) and spare parts unavailability (16%). Lack of spare parts is the most mentioned reason for unsuccessful repairs in repair cafes across the world (Repair Café International Foundation, 2020).



Producing spare parts on demand would be expensive using traditional manufacturing, which makes additive manufacturing (AM) more attractive. 3D CAD files of spare parts can easily be shared, today, however, access to such files is limited (Ford, Despeisse & Viljakainen, 2015). Sharepair wants to provide digital resources so repairers can produce spare parts with AM. To provide such resources, the necessary parts and the products they belong to should first be identified. The focus of this paper is to identify the repairs within repair communities that can be met through 3D printing spare parts.

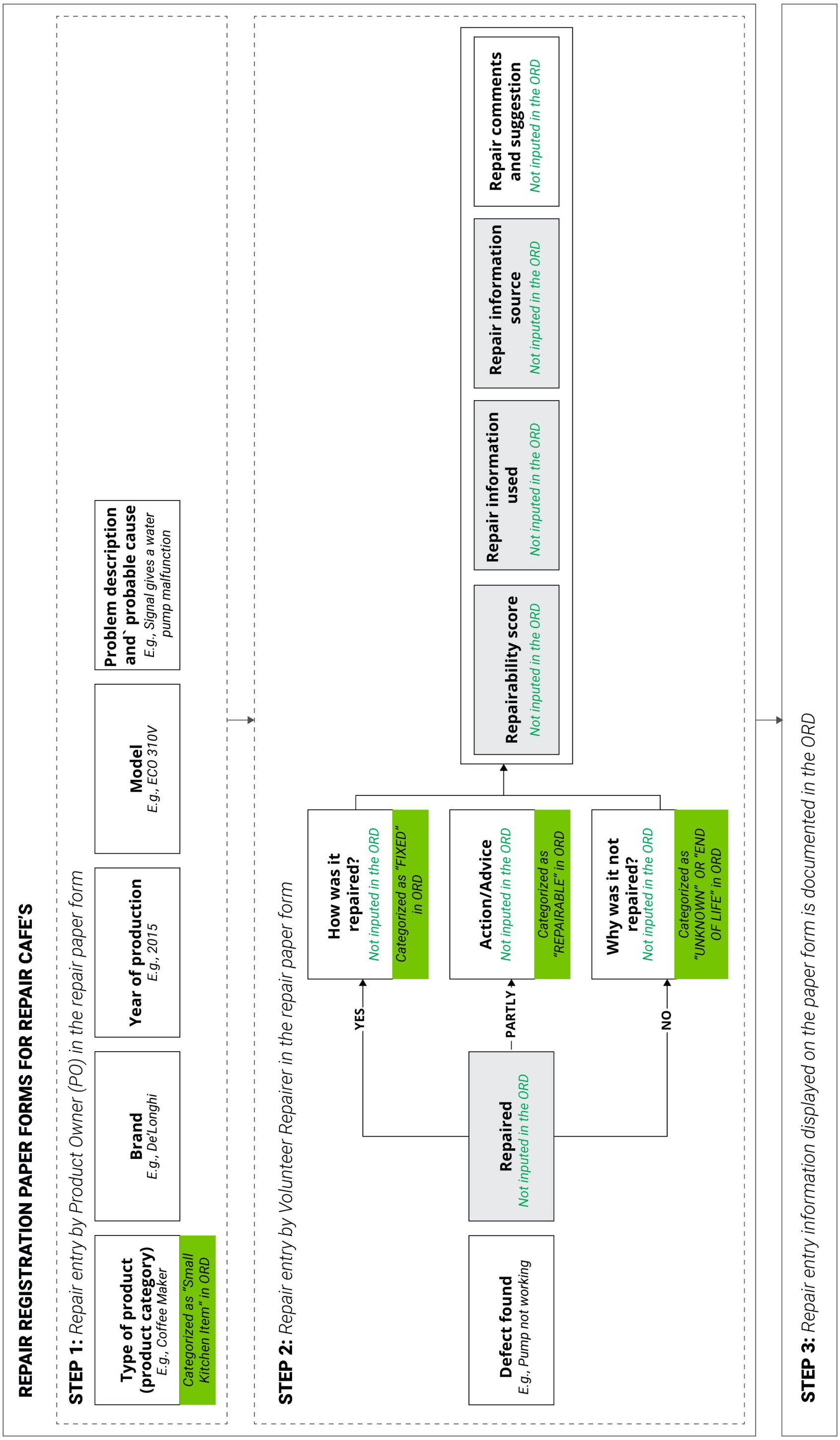



**Figure 2.1.** Current repair data entry process.

## 2.2 METHOD

Estimating the demand for 3D printed spare parts, and what products would be the best candidates for such parts, was determined by combining quantitative and qualitative analysis. The best candidates for 3D printable parts were determined by counting the most common products brought in for repair, and whether the repairs would be solvable with 3D printed spare parts.



All data was gathered from the Open Repair Database (ORD) of March 2020 (v0.1). The database contained the following fields: Data "ID" (e.g., repaircafe_2163), "Data provider" (e.g., Fixit Clinic), "Country", "Product category" (e.g., Mobile), "Product brand" (e.g., Apple), "Product model" (e.g., iPhone 6S), "Year of manufacture", "Repair status" (fixed / repairable / end of life / unknown), "Repair date", "Group Identifier" (e.g., 5073) and "Problem" (any other notes on the repair process and result). Figure 2.1 illustrates the data entry process for Repair Café's in the Netherlands, however other communities may have different processes. The ORD included 41,873 repair entries in six languages (English, French, Dutch, German, Spanish and Italian) from Open Repair Alliance communities in 18 different countries, documented from June 2012 to March 2020. Countries represented were Netherlands (43.4%), Great Britain (26.8%), Germany (11.2%), Canada (3.2%), Italy (3.1%), Belgium (3%), USA (2.2%), Norway (1.9%), Argentina (1.5%), Sweden (0.9%), France (0.5%), Spain (0.5%), Australia (0.4%), Hong-Kong (0.4%), Ireland (0.4%), Israel (0.2%), Tunisia (0.2%) and Switzerland (0%). All database entries were translated into English using Google Translate.

The "Repair status" field was a key entry, because 3D printed spare parts are only needed for products which are either "Repairable", "End of life" (see Table 2.1). "Unknown" entries could either be fixed, repairable, or end of life, and thus was not used for analysis.

The most common product categories, brands and models were determined by counting the "Product category", "Product brand" and "Product model" fields. Both "Product category" and "Product model" needed refinement before further analysis. The "Product category" field needed recategorization to align with the newest ORDS (v0.2) updated in January 2021, which is closely aligned with the EU directive on WEEE product categorization (Open Repair Data Standard, 2021; EU Directive, 2012).

For example, the "Small kitchen item" product category included both coffee makers and food processors, which have their own categories, causing redundancy. The "Product model" field contained mostly incorrect entries (most users entered the product category in this field instead of the model), so its data was refined before analysis by separating mislabeled entries from correctly labelled entries. The "Product brand" field did not require further analysis steps as it was generally filled out correctly or left blank.

**Table 2.1.** Repair Status definition (Retrieved from Open Repair Data Standard, 2021).

| Repair Status | Description |
|---|---|
| **“Fixed”** | If the repairer and owner were satisfied that the item can continue to be used. |
| **“Repairable”** | If the repairer and owner didn’t complete a repair, but identified what reasonable additional steps or professional help is needed for successful repair. |
| **“Unknown”** | An empty or zero value recorded. |
| **“End of life”** | If the repairer and the owner decided that it is not cost-effective or realistic to repair the device. |

There was no data available on spare parts. The closest data available could be found in the “Problem” field, which included open comments about the repair and why it was (not) successful. Therefore, the 3D-printable spare-parts potential was estimated by qualitative analysis of the “Problem” field entries. Because of the extensiveness of data in this field for the complete database, we used a representative subset of 1,463 repair entries constructed by selecting 5 entries per product category per year between 2012-2020. For product categories with less than 5 entries, all entries were selected. The data was not filtered by repair community, country, product model or product brand, as these varied too widely in the number of entries. The sub-selection does not perfectly mirror repair event demographics, but it was a close enough approximation.

Within the qualitative analysis the 1,463 entries were categorized in 5 repair types: (i) mechanical, (ii) electromechanical, (iii) electrical, (iv) software, and (v) unknown. Electrical, software and unknown entries were per definition unsuitable for the purpose of this research. Mechanical and electromechanical entries were further coded on their estimated 3D printability using the following categorical division: high certainty, plausible, unlikely and unknown. The categories were counted to provide quantitative estimates of repairs that might be fixed using 3D printed spare parts.

The minimum and maximum of the repair type estimates were determined by taking the outer ends of the error bars. The 3D-printability error bars overlap, so to prevent double counting, the minimum was determined by taking the low end of the high-certainty error-bars, and the maximum by taking the absolute number of high certainty and the high end of the error bar for plausible. The estimate for the whole database (represented by the qualitative subset) was made by multiplying the repair type and 3D printability percentages.

## 2.3 RESULTS

Figure 2.2 shows the number of repair entries and their status from 2012 to March 2020 (OpenRepairData V0.1, 2020). In this period, 41,873 repair entries were documented in the ORD from 229 repair communities (Repair Cafe, Restart Project, Fixit Clinic and Anstiftung). Of all 41,873 repair entries, 53% were "Fixed", 21% "Repairable", 18% "Unknown" and 8% "End of life". The yearly rate of "Fixed" and "Repairable" repairs largely remained stable over time, "Unknown" percentages increased slightly, and "End of life" percentages decreased slightly.

### 2.3.1 Product Category

Recategorization of the ORD gave 40 product categories (see Figure 2.3). The category "Small kitchen items" was by far the most often recorded entry, with 13.8% of the database total, while the average product category was 2.5% of the total. Within the "Small kitchen item" category, 51.4% of the entries were "Fixed", 15.4% "Repairable", 27.2% "Unknown", and 5.9% "End of life". Other common product categories were "Laptop", "Lamp", "Hi-Fi separates", and "Vacuum" with relatively substantial "Fixed" and "Repairable" entries. The product categories with the highest percentage "Fixed" entries were "Sewing machine", "Lamp", "Paper shredder", "Hair dryer", and "Toy".

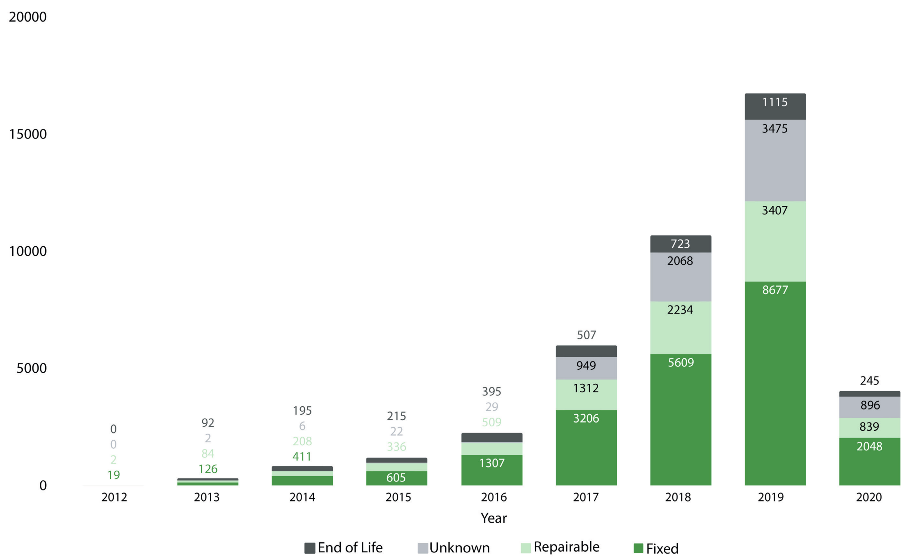



**Figure 2.2.** Number of repair entries brought in between 2012 - 2020 and their respective repair status.

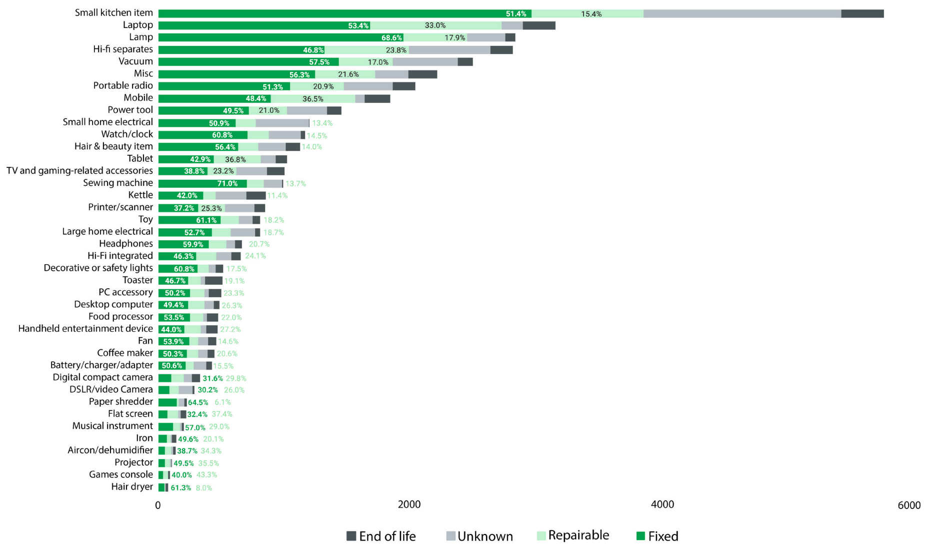



**Figure 2.3.** Number of entries in each product category, and their repair status (listed as percentages), sorted by total entry numbers.

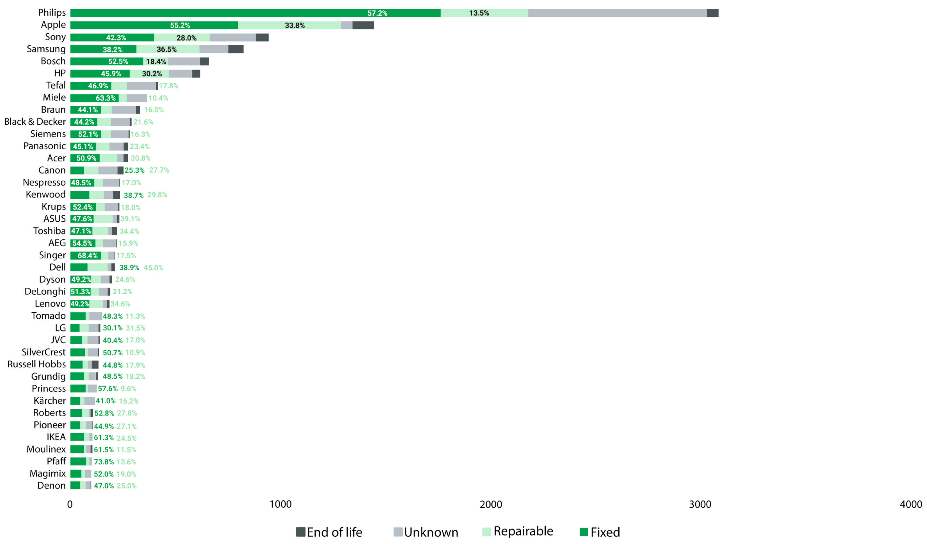



**Figure 2.4.** Number of entries for each product brand with over 100 repair entries, and their repair status, sorted by total entry numbers.

The product categories with the lowest percentage “Fixed” entries were “Flat screen”, “Digital compact camera”, and “DSLR/video camera”. Product categories with the highest “Repairable” percentage were “Games console”, “Flat screen”, “Tablet”, and “Mobile”, and the lowest were “Kettle”, “Hair dryer” and “Paper shredder”.

### 2.3.2 Product Brands

39% of database repair entries had unlabeled product brand names, of which 55% were "Fixed", 20% "Repairable", 12% "Unknown", and 13% "End of Life". Within the correctly labelled product brands, 3,234 unique brands were identified. "Philips'' was most often recorded, and other common brands recorded were "Apple" "Sony", "Samsung", and "Bosch" (see Figure 2.4). Brands with the highest "Fixed" percentages were "Pfaff", "Singer", "Miele", and "Moulinex", and the lowest were "Samsung", "LG", and "Canon". Brands with the highest "Repairable" percentages were "Dell", "Asus", and "Samsung" and the lowest were "Tornado", "Silver Crest", "Miele" and "Princess".



### 2.3.3 Product Models

72% of the total repair entries in the ORD had unlabeled product models; 28% were either correctly labelled or mislabeled. Of the entries with product model labels, 90% were mislabeled as product types (e.g., laptop), serial numbers, or only product model numbers. Only 10% with labels were correctly labelled (3% of total entries). Figure 2.5 shows the most often listed (top 10) correctly labelled product models; nine of the ten were models of iPhones. Not shown in the figure, the correctly labelled product models with the highest "Repairable" percentages were "iPad 2", "iPhone 7 Plus", "MacBook Air 13-inch 2015" and "iPhone 8". The lowest percentage "Repairable" were "iPhone 5C", Senseo HD 7840", "Senseo HD7825", and "Galaxy 2".

Similarly, Figure 2.6 shows the most often listed (top 10) mislabeled product models, starting with "Laptop", "Sewing machine", "Vacuum cleaner", "CD player", and "Coffee machine". Mislabeled product models with the highest "Fixed" percentages were "MacBook Pro 2012" and "Bike light", and the lowest were "iPod" and "Amplifier". Mislabeled product models with the highest "Repairable" percentages were "Kindle", "Galaxy" and "iPhone", and the lowest were "Coffee machine", "CD Player", "Radio" and "Lamp".

### 2.3.4 Repairs addressable by 3D printing

To estimate to what extent repairs could be met by 3D printed spare parts (plastic desktop 3D printing), a qualitative analysis of 1,463 "Repairable" entries was used. Figure 2.7 shows that of the 1,463 entries, 30% were electrical, 21% were mechanical, 14% were electromechanical and 5% were software related repair types. Thus, a total of 35% of the repair types categorically could be addressed by plastic desktop 3D printing. That is, mechanical or (possible) electro-mechanical repair types.

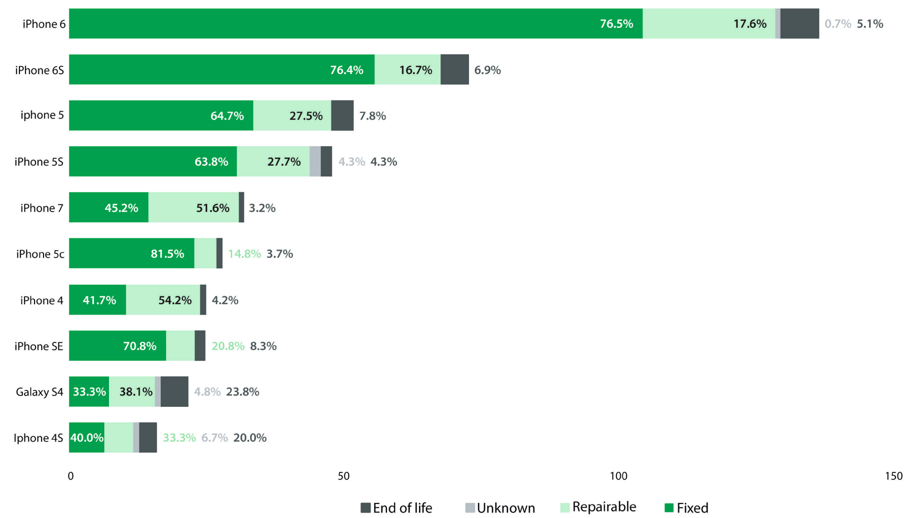



**Figure 2.5.** Number of entries for the most often listed correctly labelled product models, and their repair status, sorted by total entry numbers.

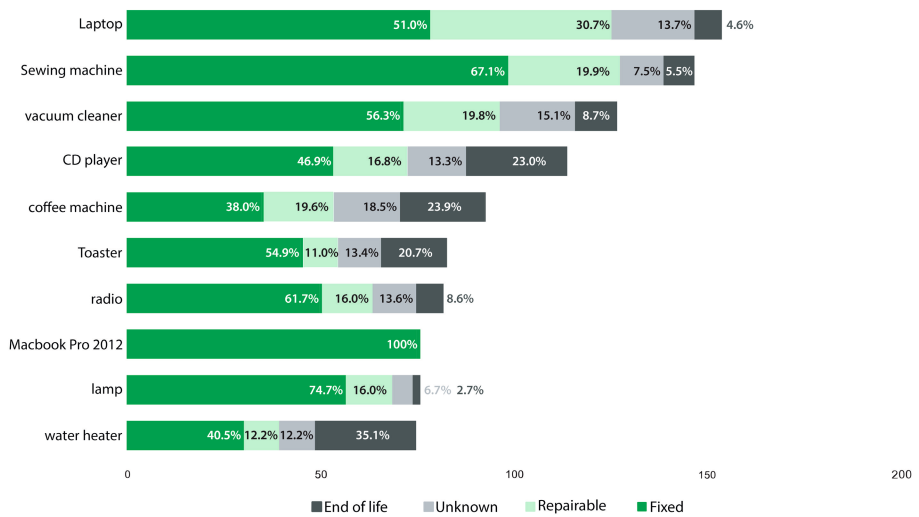



**Figure 2.6.** Number of entries for the most often listed mislabeled product models, and their repair status, sorted by total entry numbers.

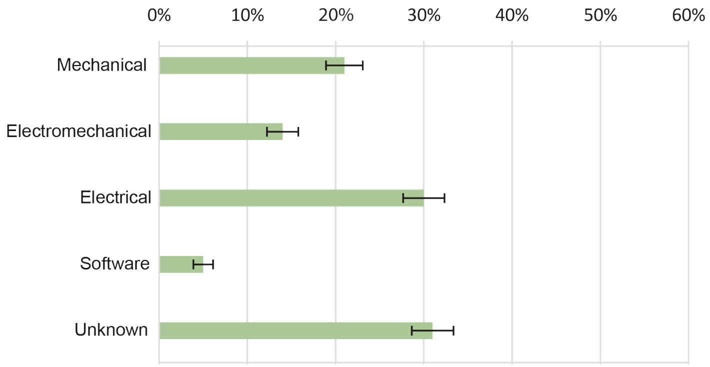



**Figure 2.7.** Different repair types within the selected data. Error bars are 95% binomial confidence intervals.

Likewise, Figure 2.8 shows the 3D printability for the mechanical and electromechanical repairs, of which 34% to 80% of mechanical repairs and 9% to 66% of electromechanical repairs might be able to be repaired with 3D printed spare parts. For the whole qualitative dataset, this would be between 7.5% - 29 %.

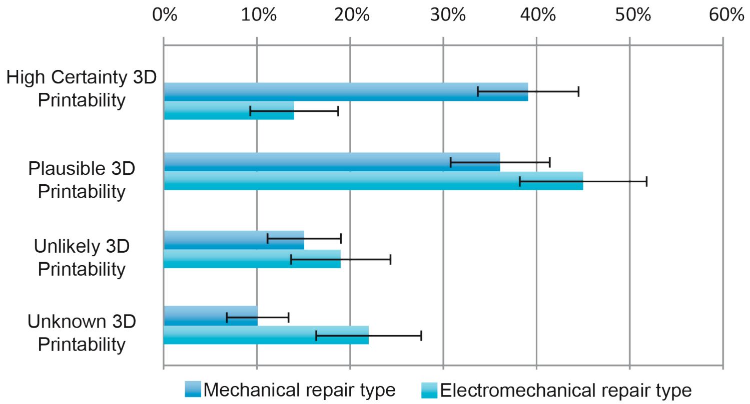



**Figure 2.8.** Different levels of assessed 3D printability within the selected data. Error bars are 95% binomial confidence intervals.

## 2.4 DISCUSSION

### 2.4.1 Product category/ model/ brand

The best product category for 3D printed spare parts is likely “Small kitchen item”, since it was by far the largest, and contained a large percentage of mechanical repairs that could arguably be repaired with 3D printed spare parts. However, this category contained a great diversity of products, and thus a great diversity of parts that would need to be 3D modeled and tested.

Several brands, including Philips, Apple, Sony, and Samsung, had high numbers of repair entries. Notably, Apple, Sony, and Samsung also had high percentages of entries labelled as “Repairable”, but with many of their products being primarily electronic and the possibilities of being fixed by 3D printed spare parts are limited. Similarly, the product models which were correctly labelled were almost all smartphones, so this did not help find targets for 3D printed parts.

The most-mentioned product categories and information on product models and brands are currently insufficient to plan the generation of 3D printed spare part libraries. The current categorization lacks distinctness or allows for a large number of mislabeled entries (e.g., the ambiguity of the “Miscellaneous” category, “Small kitchen item” being a separate category from “Toaster” and “Kettle”). To improve this, we recommend using the European Directive WEEE categorization (Directive 2012/19/EU), as a guide to reframe the “Product category” entry, since it provides more granularity. In addition, we recommend providing examples of product models, to avoid the currently rampant mislabeling.

### 2.4.2 Repair Status

“Fixed” products are unlikely to need 3D printed spare parts, so most opportunities for repair with 3D printing were estimated to be in entries labelled as “Repairable”. There are potential opportunities in the “Unknown” and “End of life” categories, but these have insufficient data to conclude. This “Repair Status” data could be clarified by asking what would be needed to finish a repair marked as “Repairable”. We recommend request further information to justify the selected label, specifically when it is labelled as “Repairable” (E.g., spare part is necessary; Figure 2.9).

### 2.4.3 3D Printability

Between 7.5% to 29% of all recorded repairs from these repair communities might be helped by 3D printed spare parts, when counting “highly likely” and “plausible” entries within those labelled as “repairable” with “mechanical”, and “electromechanical” repairs. These percentages are an initial estimate of 3D printability, but this also depends on the functional and performance requirements of each part. Further analysis is required to consider the specifics of each component. This information is not currently available in the ORD.

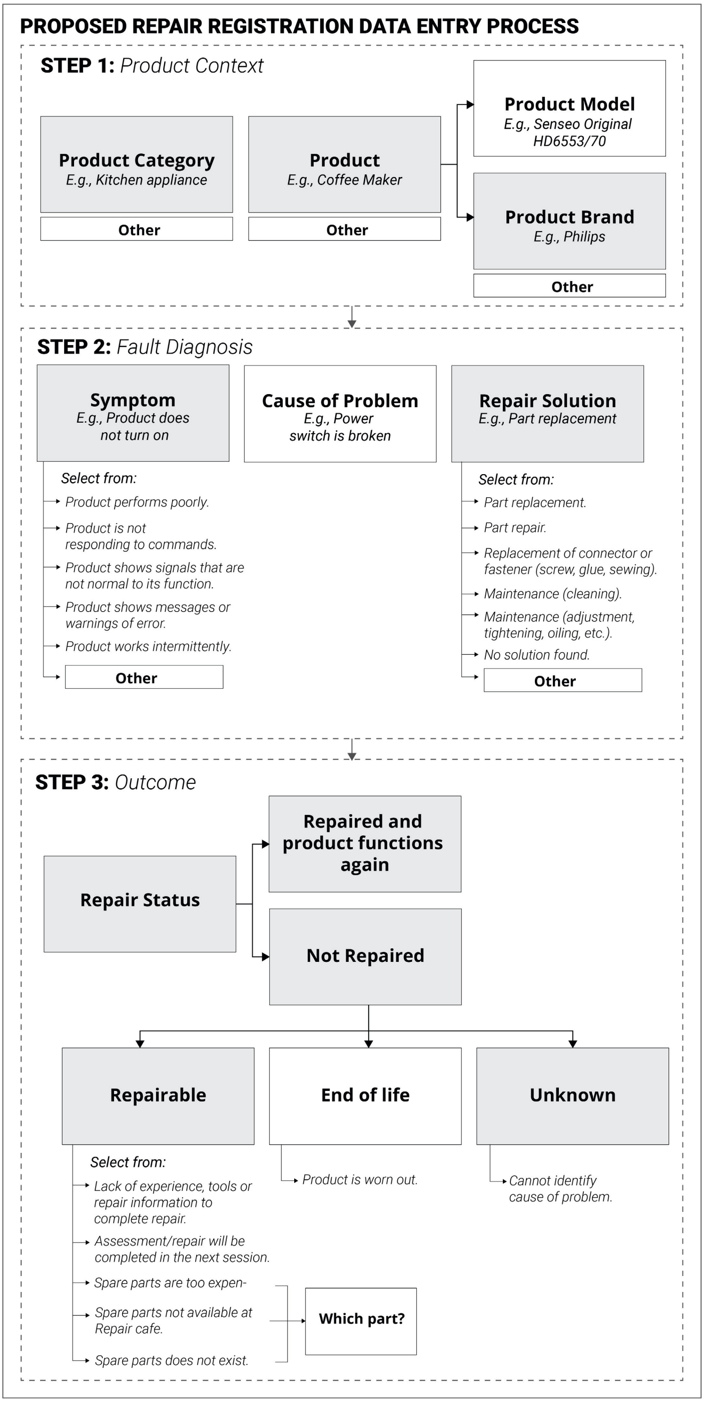



**Figure 2.9.** Proposed repair registration data entry process. Categorization of symptoms based on Pozo et al., 2020.

### 2.4.4 ORD Limitations

Entries within the ORD were often mislabeled or incomplete, in many cases due to vagueness of the entry fields, as mentioned above. In addition, a large part of the repair data was entered in multiple languages in open comments, without pre-categorization. In consequence, considerable data processing and interpretation are required to analyze it, leading to information getting lost in translation and inconsistent data sets. Table 2.2 shows examples of “Problem” field comments which lacked detail or included information that should have been entered in other fields.

**Table 2.2.** Example of comments in the “Problem” field in the ORD.

| Fixed | Repairable |
| --- | --- |
| “Bolt does not work” | “Failure” |
| “cut” | “Clogged element” |
| “HVAC 1.1kg” | “Yes ~ Does not” |
| “Changed capacitor” | “Valve is broken” |
| “Broken riser pipe break” | “PCB Board faulty ~ Not charging the fence” |
| **Unknown** | **End of Life** |
| “Unknown ~ Do nothing” | “Coffee machine leaks” |
| “Makes too much noise” | “Engine broken” |
| “Stops halfway” | “Heating defective” |
| “Broken water filter- does not filter” | “Fell out ON-OFF button” |
| “Clutch/drive connection failed” | “Blenders - power broken button” |

We estimate these limitations arise mainly from the repair registration form and data entry process; which asks an extensive number of open questions that do not correspond to the database, is filled in by more than one individual per entry, and is recorded using a paper form which is later manually digitized (Figure 2.1).

We recommend the following for the streamlining of the entry process and to facilitate the identification for the need of 3D printed spare parts: switching the entry process into a directly digital format, limiting the number of people entering information to only the volunteer repairer, requesting only relevant information in the form of closed questions with pre categorized fields, and allowing the specification of spare part requirements within the “Repair Status” field. (See Figure 2.9) We also recommend testing and validating the recommended process with users in repair communities. Such revisions of ORD data entry would not only help expose opportunities for 3D printing in repair, but would also help expose opportunities to improve the repairability of products in many other ways.

## 2.5 CONCLUSION

The goal of this paper was to find opportunities for 3D printing of spare parts for repair communities by analyzing repair needs in the Open Repair Database from the Open Repair Alliance. The objectives were to estimate how many repairs 3D printing could address, and what kinds of products should be targeted for creating libraries of 3D printable parts.

To answer the first question, qualitative coding of repair problems showed 7.5% - 29% of non-repaired items in repair cafés might benefit from 3D printed spare parts. Suitable repairs were mainly estimated to be mechanical, so mechanical parts of kitchen appliances would be the priority when constructing a library of downloadable 3D CAD files of spare parts.

To answer the second question, quantitative analysis showed “Small kitchen item”, “Laptop”, and “Lamp” were the most common product categories. “Small kitchen item” had many “Repairable” and many mechanical repair entries, which made it a promising target for 3D printed spare parts. Product model data was too often mislabeled to be trustworthy, and the most common correctly labeled product models were electronic, thus unlikely candidates for 3D printed spare parts. Common brands included Philips, Apple, and Sony, but their products were also mainly electronic. Therefore, specific product models or brands were not useful to target.

This study’s effectiveness was limited by significant amounts of incomplete or incorrect data. Many entries had unidentifiable product models and/or brands, and most product models were incorrectly labelled as either a product sub-category, serial number, or just product model number. Information on product fault and spare part use was also limited, which made it difficult to conclude if parts could be printable. To better estimate possibilities for 3D-printing for repair in the future, and provide other insights into product repairability, we recommend improving the data entry process. This can be done by streamlining the data entry process and minimizing the number of open questions.

Repair is one of many ways to create a more sustainable world with longer-lasting products. Although 3D-printing cannot solve all repair problems, by further testing and developing 3D-printing for Repair, we can make a positive impact by saving product lives.

## 2.6 REFERENCES

Cole, C., Cooper, T., & Gnanapragasam, A. (2017). Extending product lifetimes through WEEE reuse and repair: Opportunities and challenges in the UK. *2016 Electronics Goes Green 2016+, EGG 2016*, 1–9. https://doi.org/10.1109/EGG.2016.7829857

Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE) Text with EEA relevance.

Ford, S., Despeisse, M., & Viljakainen, A. (2015). Extending product life through additive manufacturing: The sustainability implications. *Global Cleaner Production and Consumption Conference*, December, 1–4. https://www.researchgate.net/publication/282075975_Extending_product_life_through_additive_manufacturing_The_sustainability_implications

King, A. M., Burgess, S. C., Ijomah, W., & McMahon, C. A. (2006). Reducing waste: Repair, recondition, remanufacture or recycle? *Sustainable Development*, *14*(4), 257–267. https://doi.org/10.1002/sd.271

Pérez-Belis, V., Braulio-Gonzalo, M., Juan, P., & Bovea, M. D. (2017). Consumer attitude towards the repair and the second-hand purchase of small household electrical and electronic equipment. A Spanish case study. *Journal of Cleaner Production, 158*, 261–275. https://doi.org/10.1016/j.jclepro.2017.04.143

Pozo Arcos, B., Bakker, C., Flipsen, B., & Balkenende, R. (2020). Practices of fault diagnosis in household appliances: Insights for design. *Journal of Cleaner Production, 265*, 121812. https://doi.org/10.1016/j.jclepro.2020.121812

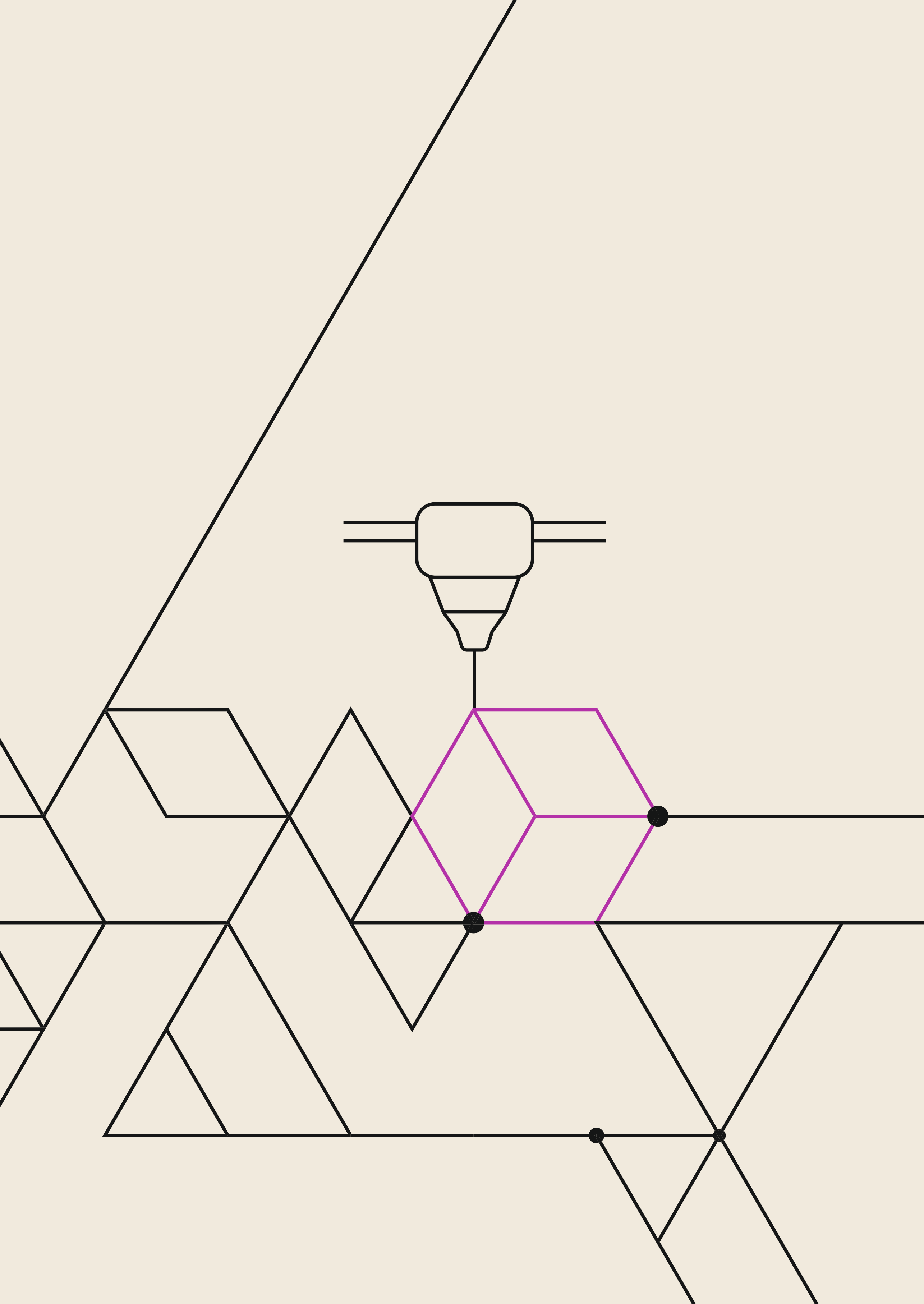
Repair Cafe International Foundation. (2020). *Repair Monitor - Analysis Results 2019*. https://repaircafe.org/en/wp-content/uploads/sites/2/2020/05/RepairMonitor_analysis_2019_05052020_ENGLISH.pdf

Sabbaghi, M., Esmaeilian, B., Cade, W., Wiens, K., & Behdad, S. (2016). Business outcomes of product repairability: A survey-based study of consumer repair experiences. *Resources, Conservation and Recycling, 109*, 114–122. https://doi.org/10.1016/j.resconrec.2016.02.014

Scott, K. A., & Weaver, S. T. (2014). To Repair or Not to Repair: What is the Motivation? *Journal of Research for Consumers*, January 2014, 1–31.

Open Repair Data_V0.1. *Aggregate dataset 2020-3-31*. https://github.com/openrepair /data/tree/master/aggregated/202003

Open Repair Data Standard. 1st January 2021. https://standard.openrepair.org/ document.html.



CHAPTER 3

# 3D Printing for Repair: An Approach for Enhancing Repair

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## ABSTRACT

The availability and storage of spare parts are the main barriers to product repair. One possibility would be to 3D print spare parts, which would also enable the repair of products not intended to be repaired. Besides manufacturers, 3D printing spare parts is an interesting option for self-repair by consumers. However, the digitisation of spare parts for 3D printing is a challenge. There is little guidance on how to make a 3D-printed version of the original part. This paper establishes a framework through a literature review and experimental study to describe how to use 3D printing to produce spare parts for repair. Additionally, qualitative data coding was used to find the influence of previous experience, process implementation, and part complexity on the overall success of the 3D printing for repair (3DPfR) process. Our study showed that the 3DPfR process can be described as an iterative design for an additive manufacturing process that is integrated into a repair process. Additionally, it was found that the incorrect implementation of process steps was the most important predictor of the repair result. The steps that were performed incorrectly the most were synthesising design concepts (64%) and validating print quality (also 64%).

## 3.1 INTRODUCTION

Repair is an essential step in "slowing the flow" of products in a circular economy (Cooper, 2020). To promote reparability for ordinary consumers, the European Commission has implemented the first acts to ensure the availability of spare parts for consumer products such as dishwashers and fridges for a longer time period (Šajn, 2022). Increasing the availability of spare parts means that original equipment manufacturers (OEMs) need to find cost-effective ways to store spare parts for older products (Svensson-Hoglund et al., 2021). Instead of storage, an alternative solution would be to make the spare parts on demand: for example, through additive manufacturing (Pérès & Noyes, 2006; Sasson & Johnson, 2016). Three-dimensional printing enables the continued availability of these parts long after storage becomes impractical (Kim et al., 2019), so, potentially, a manufacturer could support products indefinitely (Holmström & Gutowski, 2017). Additionally, 3D-printed spare parts could reduce repair times, labour costs, storage costs, material use, and transportation. In a study by Chekurov et al. (Chekurov et al., 2018), OEM participants estimated that between 2% and 75% of their companies' spare part libraries could be acceptably manufactured with 3D printing, with most answers between 5% and 10%. More parts can be expected to become feasible in the future with the rapid advance of 3D printing (Chekurov & Salmi, 2017).



Current research mainly focuses on 3D printing spare parts by OEMs in industries such as aerospace, automotive, and machine tool production (Attaran, 2017). Topics include supply chain benefits and configuration, economic benefits, and sustainability benefits (Kunovjanek et al., 2020). Other studies focus on the classification and selection of suitable spare parts (Chaudhuri et al., 2020). Three-dimensional printing is good at producing complex geometry with high design flexibility and customisation (Ngo et al., 2018). A part can be tailored to its function with an optimal balance between strength and material use (Zijm et al., 2019), which means the part can be improved compared to its original design (S. Yang et al., 2015). Additionally, it gives the opportunity to modify and update the parts after the initial production has ceased (Attaran, 2017; Holmström & Gutowski, 2017; Sauerwein et al., 2018).

Besides OEMs, 3D printing spare parts is also an interesting option for self-repair by consumers. Consumer interest in repair is increasing (Scott & Weaver, 2014), but barriers to successful self-repair are the complicated repair process, expensive spare parts, and spare part unavailability (Sabbaghi et al., 2016). The 3D printing of spare parts would enable repair where it normally is not intended by the manufacturer (Sauerwein et al., 2019). A study of the Open Repair Database (ORD) showed that 7.5–29% of non-repaired items in repair cafés could benefit from 3D-printed spare parts (Samenjo et al., 2021). If OEMs do not provide the needed spare parts, customers might reverse-engineer the parts they need and share their instructions online (Kietzmann et al., 2015).

However, the digitisation of spare parts for 3D printing is a challenge for both OEMs and consumers. Missing or insufficient availability of part data and 3D models can be significant obstacles in the digitisation process (Chaudhuri et al., 2020; Chekurov et al., 2018; Knofius et al., 2016). There is also a large number of spare parts that will only be feasible for 3D printing after significant redesign efforts (Frandsen et al., 2020; Holmström & Gutowski, 2017), such as geometry or material optimisation (Chaudhuri et al., 2020; Westerweel et al., 2018). As part properties are often dependent on the geometrical design, design rules for 3D printing are not easily generalised over different products and printing methods (Westerweel et al., 2018; L. Yang et al., 2017). Instead, considerable skill is required to determine how part function and geometry are linked, so the question is how to support design engineers in the redesign process (Ganter et al., 2021).

Specific guidance on redesigning existing parts for 3D printing is limited. There are numerous frameworks on design for additive manufacturing, such as Haruna & Jiang (2020), Leary (2020), Vaneker et al. (2020), and Wiberg et al. (2019). However, none of these frameworks has been constructed with the repair of existing (spare) parts in mind. There are studies focused more specifically on using 3D printing in repair, such as Kim et al. (2019), Lindemann et al. (2015), Park (2015), and Terzioğlu et al. (2016). The framework by Kim et al. (2019) describes the partial repair of parts by comparing the damaged part against the whole parts and printing the difference. However, this assumes that a digital design of the file is already available. The methodology by Lindemann et al. (2015) does offer support for redesigning an existing part for printing but represents the process as a black box. This makes it difficult to retrieve insights for process guidance. Park (2015) and Terzioğlu et al. (2016) present several consumer products repaired with 3D-printed parts in the context of consumer self-repair. However, these two studies mainly present the final results and not the process of developing the parts. Outside of the scientific literature, there are a few guides that describe the process of 3D printing a spare part by consumers, such as the work by Lorenzen & Paape (2018) and the master thesis by Beerkens (2017a).

More insight into the process of 3D printing for repair (3DPfR) is needed to understand what the possibilities and challenges are. A framework needs to be developed that describes the steps of translating an existing part into a 3D-printed replacement part. Thus, the research questions of this paper are:

**RQ 1.** How can the 3DPfR process that leads to a successful repair be described?

**RQ 2.** What is the influence of previous experience, process implementation, and part complexity on the overall success of the 3DPfR process?

To address the first RQ, we developed a framework through a literature review and experimental case study. This framework was applied empirically with a group of students to test its effectiveness, and the results were analysed to find how experience, process factors, and part complexity influenced the overall repair success.

## 3.2 METHOD

### 3.2.1 Establishing a Framework for 3DPfR



The 3D printing for repair (3DPfR) process was formalised by setting up a framework based on a literature review and experimental study. The first selection of process steps was made by reviewing the "grey" literature and then verifying and expanding this through scientific literature from similar fields. Then, an in-depth experimental design study was performed to validate and refine the framework. This was an iterative process, and the results are not presented in chronological order.

The scientific literature review used frameworks on product design, design for additive manufacturing, and repair in design. These were deemed the closest fields, and the 3DPfR process requires them all to overlap. The literature frameworks were found in Science Direct using search strings that combined field-relevant keywords with "framework". For example, "product repair AND framework" or "design for added manufacturing AND framework". Only recent (2015 and later) and fundamental works were considered. The papers were scanned for frameworks, and papers without a framework were discarded.

The found frameworks were filtered based on their content and size (number of steps). The frameworks selected were aimed at explaining the process and describing the activities. This ruled out frameworks aimed at, for example, stakeholder mapping or data processing but included design frameworks and schematic representations. Additionally, the selected frameworks were 15 steps or fewer to make sure the frameworks were not too detailed but instead general enough to be applied to our topic. The final selection of frameworks was limited to two frameworks per field.

The framework steps were presented as flowcharts beside each other to visualise framework similarities and differences. Frameworks were unaltered, but some steps were rephrased to highlight corresponding steps. The process descriptions and case studies in each paper were studied to gain additional process insights. A first selection of 3DPfR process steps was then made by selecting relevant steps from the reviewed frameworks and omitting steps not relevant to 3DPfR. When formulating the 3DPfR process steps, care was taken to avoid FDM-specific steps or details and rather translate all considerations to principles that would be as universal as possible across print technologies for repairing household consumer products. They may be generalised to other fields as well.

A small experimental case study was used to verify the literature review and to locate possible gaps in earlier works. Two researchers independently created 3D-printed replacement parts for two repair cases and documented their process steps. The repairs were carried out with an Ultimaker 5+ fused deposition modelling (FDM) printer (Ultimaker, Zaltbommel, The Netherlands) using standard polylactic acid (PLA) filament. Additionally, the number of iterations, time spent, repair results, and design changes for each case were tracked. These insights were used to structure the research focus of RQ2.

Afterwards, the documented process steps were compared to the selected 3DPfR process steps. The selected steps were extended and restructured accordingly and grouped into sections. These sections of steps were further developed for cohesiveness and clarity. This resulted in a draft of the framework that could be tested with users in RQ2.

The selection criteria that were used to select the experimental study cases were (a) it concerned a common electronic consumer product, (b) it had a broken part, and (c) it was a mechanical repair (e.g., no electronic components). The selected repairs were a water kettle of an unknown brand with a broken switch and broken locking mechanism and a Microsoft Surface keyboard with a broken key. The kettle was estimated as feasible, whereas the keyboard was estimated as likely to fail. The intended failure was used to test the limits of 3DPfR and to find process steps that might only be required for more complex repair cases.

### 3.2.2 Identifying Factors for Successful Repair

To measure the impact of previous experience, process implementation, and part complexity, we collected data during a practicum on 3DPfR. This three-day online practicum was based on the constructed 3DPfR framework. The participants were 48 3rd-year bachelor students from various studies following the TU Delft minor "Designing Sustainable Transition". The workshop requested participants to run through one iteration cycle of our 3DPfR process framework. Participants independently made a 3D-printed part for a (broken) product of their choice, aided by lectures and a written guide. The parts were printed on an Ultimaker 5+ FDM printer using standard PLA filament, due to the availability of these printers and materials in the practicum location, plus their general ubiquity and accessibility in maker spaces. Only cases where all deliverables were complete were used, which resulted in a dataset of 45 cases. Qualitative data were gathered from the workshop deliverables and coded. The quantitative study counted and graphed the relevant codes, and an additional qualitative study validated the quantitative data patterns found in the quantitative graphs.

The qualitative data were gathered from the workshop deliverables. These were, for each participant, four presentation slides with their insights per process phase, a reflection text, a 3D CAD model (.STL extension), and printing settings (printing resolution, printing speed, infill percentage, and print orientation). The data codes used represented general repair data, previous experience, process implementation, and part complexity.



The qualitative dataset was coded independently by two people using a predetermined coding table. The coding table was constructed by defining when a certain process step or part requirement can be considered applicable. For process steps, this included definitions of whether it was performed correctly or incorrectly; for part requirements, this included definitions of when a part met the requirement. Appendix A lists the definitions of correct/incorrect for each process step and applicable/not applicable for each part requirement. The student presentation slides were then coded by comparing the data to the definitions of the coding table and selecting the corresponding code. Table 3.1 presents a summary of the coding table; the full coding table with explanations and examples can be found in Appendix A. The coding table was constructed before coding, but codes were adjusted and recoded where needed while coding. The coding agreement of the final coded dataset was 0.81 using Cohen's Kappa. For the final data analysis, one of the two coding datasets was chosen at random because of their close agreement.

**Table 3.1.** Summary of the coding table.

| Topic | Code | Options |
|---|---|---|
| **General** | Repair result | Success/Failure/Unknown |
| | Repair type | Repair/Added Value/Both |
| **Previous experience** | Previous experience | None/Only CAD/Both CAD and 3D printing |
| **Process implementation** | Analyse/Redesign/Manufacture/ Test process steps<br>E.g., Define tolerance/fit | Incorrect/Correct/Not applicable * |
| **Part complexity** | Part completeness | Complete/Broken/Missing |
| | Part suitability | Very suitable/Somewhat suitable/ Unsuitable |
| | Part requirements<br>E.g., Flexibility | Yes/No |
| | Unsuitable part requirements<br>E.g., Part mechanical performance too high | Yes/No |

The quantitative data analysis counted and graphed the relevant codes and interpreted the data by comparing numbers and Adjusted Wald confidence intervals. Codes can only occur once per case, so no adjustment for double-counting was needed. The data were graphed as bar charts with Adjusted Wald confidence intervals visualised as error bars. The Adjusted Wald confidence interval was chosen because it yields coverage probabilities close to nominal confidence levels, even for very small sample sizes (Agresti & Coull, 1998). All Adjusted Wald intervals were calculated at 95% confidence.

The qualitative data analysis sought to validate the significant effects of the quantitative data. When quantitative differences appeared statistically significant, the text of student presentations and reflections was scanned for mentions of the relevant data codes and patterns. These quotes were collected and tagged with their corresponding codes. Then, the qualitative quotes were compared with the quantitative analysis to validate apparent statistical significance, and, ideally, provide explanations for how or why. Finally, all qualitative codes were scanned for strong patterns that did not appear significant in the quantitative analysis to validate that the quantitative analysis did not miss important factors.

## 3.3 RESULTS

### 3.3.1 The 3DPfR Framework

This section describes the selection of 3DPfR process steps based on the literature review. This selection is then adjusted and validated based on insights from the small experimental case study.

#### 3.3.1.1 Literature review

Figure 3.1 summarises the insights from the literature to formalise the 3D printing for repair (3DPfR) process for DIY repairers. The literature framework flowcharts are grouped per topic. Activities (flowchart boxes) on the same row are similar, whereas a gap indicates framework differences. If a framework was characterised as an iterative process, it is mentioned in the last row.

*Selected Steps That Appeared in All Frameworks*

Figure 3.1 shows that (almost) all frameworks considered in this literature review included some form of the following activities, which were thus selected as 3DPfR process steps: analyse part and product, design synthesis and digitise part, prepare print and print part, repair, test part performance, and iterate.

Analyse part and product studies the part and product in detail to come to the part requirements. Analysis of part topology (refers to how the part is connected within the product (Leary, 2020)), part geometry (refers to what the part itself looks like (Leary, 2020)), and part functionality (Beerkens, 2017a; Leary, 2020) shows what part features and functions are critical, and what can be simplified (Beerkens, 2017a; Haruna & Jiang, 2020). Reverse engineering the original part can restructure the initial design intentions. This helps to find the best design and manufacturing approach and to indicate process difficulty (Beerkens, 2017a).

Design synthesis and digitise part, respectively, ideate and model a part that meets the part requirements from the analysis. A successful design cycle is supported by and implements other phases of the design cycle (Roozenburg & Eekels, 1995). Idea generation involves creative thinking to come up with suitable repair solutions. The repairer needs to make aesthetic and structural decisions while considering the reproducibility of the repair (Terzioğlu & Wever, 2021). Additionally, the part design should be adjusted and optimised for 3D printing. Parts can be combined or segmented or simplified to an easier geometry with the same function (Haruna & Jiang, 2020). For large or complex parts, only the defective segment could be printed (Lorenzen & Paape, 2018).



Prepare print and print part turn the digital model into a physical object through 3D printing. The (digital) preparation steps for this include exporting the CAD file as an STL file, which can be sliced to generate printer toolpaths (Beerkens, 2017c; Leary, 2020). Part slicing can be influenced by printer settings, such as support, infill, layer thickness, wall thickness, and bed adhesion. Printer settings influence part functionality and aesthetics, as well as printing ease, printing time, and material use (Beerkens, 2017c).

Repair restores the product to a functional state using the manufactured part. This involves component repair/replacement, which leads to an altered functional product (Pozo Arcos et al., 2020). It can also be seen as an implementation phase that implements the developed decisions and solutions to restore product functionality (Terzioğlu & Wever, 2021).

Test part performance finds out how the printed part compares against the set design requirements. There will always be differences between the expected and desired properties. Judging whether these differences are acceptable is difficult, as there are a large number of properties involved (Roozenburg & Eekels, 1995). Testing the part can include checking print errors and part appearance (Beerkens, 2017c), confirming correct part dimensions, and proof testing (destructive or non-destructive) the mechanical response (Leary, 2020).

Iterate is an inherent step in any design process (Roozenburg & Eekels, 1995). Besides the design process, iteration could also take place in the fault diagnosis (Pozo Arcos et al., 2020). Through these iterative feedback loops, design decisions can be reviewed as the design progresses (Leary, 2020).

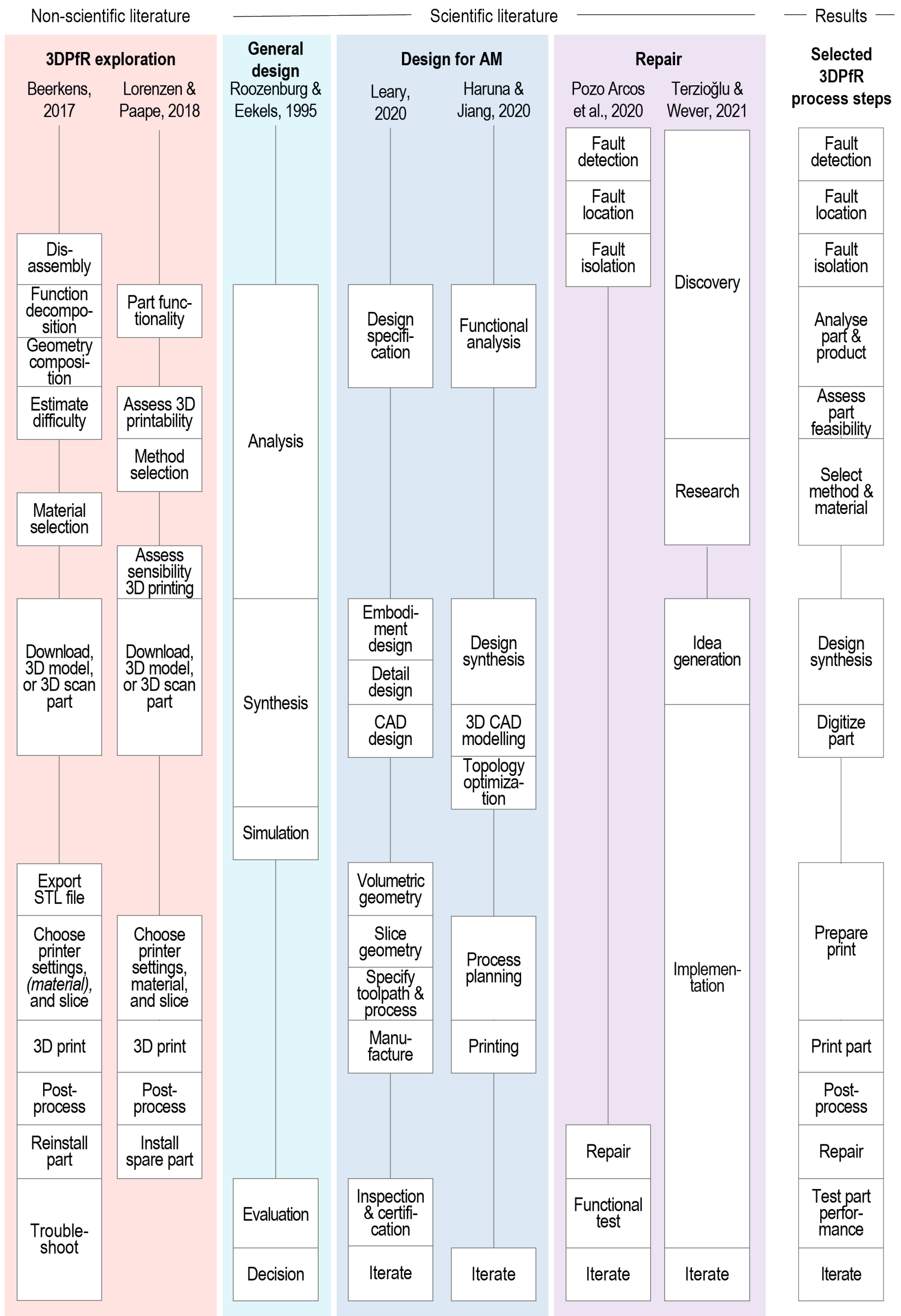


**Figure 3.1.** Overview of relevant frameworks from the literature study and the selected 3DPfR steps (Beerkens, 2017a; Haruna & Jiang, 2020; Leary, 2020; Lorenzen & Paape, 2018; Pozo Arcos et al., 2020; Roozenburg & Eekels, 1995; Terzioğlu & Wever, 2021).

*Selected Steps That Appeared in Some Frameworks*

The 3DPfR process steps selection also includes activities that were not present in all frameworks, but that were still deemed valuable for guidance. These were fault detection, fault location, fault isolation, assess part feasibility, select method and material, and post-process.

Fault diagnosis is an essential repair step to find the broken part. Fault diagnosis can be divided into fault detection, fault location, and fault isolation (Pozo Arcos et al., 2020). In these steps, the symptoms, causes of failure, and corrective actions are studied and tested to come to the repair diagnosis. Reverse engineering how the product was used and damaged helps to prevent the same damage in the repair redesign (Terzioğlu & Wever, 2021).



Assess part feasibility considers both the technical and practical feasibility of successfully 3D printing the part, such as 3D file availability and the technical limits of 3D printing (Lorenzen & Paape, 2018). Part feasibility should consider the required time, amount of design work, economic effort, resource consumption, environmental impacts, perceived value, and emotional meaning (Beerkens, 2017b; Lorenzen & Paape, 2018; Terzioğlu & Wever, 2021). Complex, challenging, or incomplete parts will make the redesign process more difficult and time-consuming (Beerkens, 2017b). For non-feasible parts, alternative approaches might be considered, such as using another manufacturing method (Lorenzen & Paape, 2018).

Select method and material should take place early in the process, as it will influence the design process. Various 3D printing processes have different construction methods, which will influence the design possibilities (Lorenzen & Paape, 2018). Additionally, material choice greatly influences the part's performance and functioning (Beerkens, 2017a).

Post-processing is often needed to meet functional and aesthetic part requirements. It includes removing support structures, joining segmented part sections (plugging, screwing, clipping, or glueing), drilling, milling, or lubrication (Lorenzen & Paape, 2018). Surface finish and aesthetics can be adjusted through, for example, sanding, polishing, coating, or painting (Beerkens, 2017c).

*Steps That Were Not Selected*

There were also activities that were mentioned in some literature frameworks but which we did not select. These were assess 3D printing sensibility, topological optimisation, simulation, and certification.

Assess 3D printing sensibility (Lorenzen & Paape, 2018) was excluded because the difference between feasibility and sensibility is too minor. Sensibility determines whether it would be better to buy the original spare part, buy a new product, or use a different manufacturing method (Lorenzen & Paape, 2018). However, most feasibility assessments will include sensibility aspects, so it does not make sense to highlight it as a separate step. Instead, it is marked as an additional insight for shaping the assess part feasibility step.

Topology optimisation (Haruna & Jiang, 2020) was excluded because this is generally not accessible for DIY repair. It assumes an advanced additive manufacturing (AM) process, high skill level, and high-end equipment. Additionally, these methods focus on general AM performance, rather than repair.

Simulation (Roozenburg & Eekels, 1995) was excluded because the availability of 3D printing simulation tools for consumers is currently limited. Furthermore, 3D printing has a short lead time and high flexibility compared to traditional manufacturing. This makes it easier to test the printed part instead of predicting part behaviour through logical reasoning or model tests.

Certification (Leary, 2020) was excluded because the certification of 3D printing is almost non-existing at the moment. Additionally, within non-licensed repair, consumers will not be able to certify the parts themselves.

*Additional Insights*

Three-dimensional printing should not be the first step in replacing a broken part. If there are already produced and affordable spare parts available, it makes more sense to use those instead Only if the replacement part is not available or disproportionately expensive, it becomes interesting to 3D print it (Lorenzen & Paape, 2018). It is also good to consider the longevity and reparability of the repaired product. The repair might strengthen the product or make it more susceptible to damage. Similarly, the repair solution can make product repair easier or more difficult and can also impact the (perceived) product value and aesthetics (Terzioğlu & Wever, 2021).

#### 3.3.1.2 Experimental Study

The selected process steps from the literature review were tested in the experimental study. Table 3.2 shows the process results, and Figure 3.2 shows the original part and redesigned 3D-printed part for all repair cases. Two out of three part replacements succeeded and one failed, which matched our initial feasibility expectation.

**Table 3.2.** Repair case results.

| Product and Part | Repair Result | No. of Iterations | Total Time Spent * | Print Time Final Iteration | Redesign Approach |
|---|---|---|---|---|---|
| **Kettle - switch** | Success | 4 | 20 h | 1 h 53 min | Strengthening of thin sections<br>Simplify complex geometry |
| **Kettle - locking ring** | Success, with heat-resistant PLA | 5 | 21 h | 3 h 5 min | Strengthening of vertically printed and thin sections |
| **Keyboard - key attachment** | Fail | 7 | 35 h | 1 h 4 min | Simplify complex geometry<br>Completely redesign part topology |

** All iterations together, including printer setup but excluding the machine printing time.*

Redesigning each part required at least four iterations with a total of 20 h work. The failed keyboard repair was stopped after seven iterations with 35 h work, as it yielded no more additional insights. For the kettle switch, the thickness of the arms was increased, and complex curvature was simplified. For the kettle locking ring, the vertically printed sections were fortified by increasing the thickness. The keyboard attachment mechanism required a complete redesign, as the thin part geometry ($\leq$ 0.5 mm) could not be printed.

The process flow of both repair study cases was a near match with the literature review framework. Only a few changes were made to the selected process steps of the literature review. These changes will be discussed below, as well as additional insights from the studied repairs.

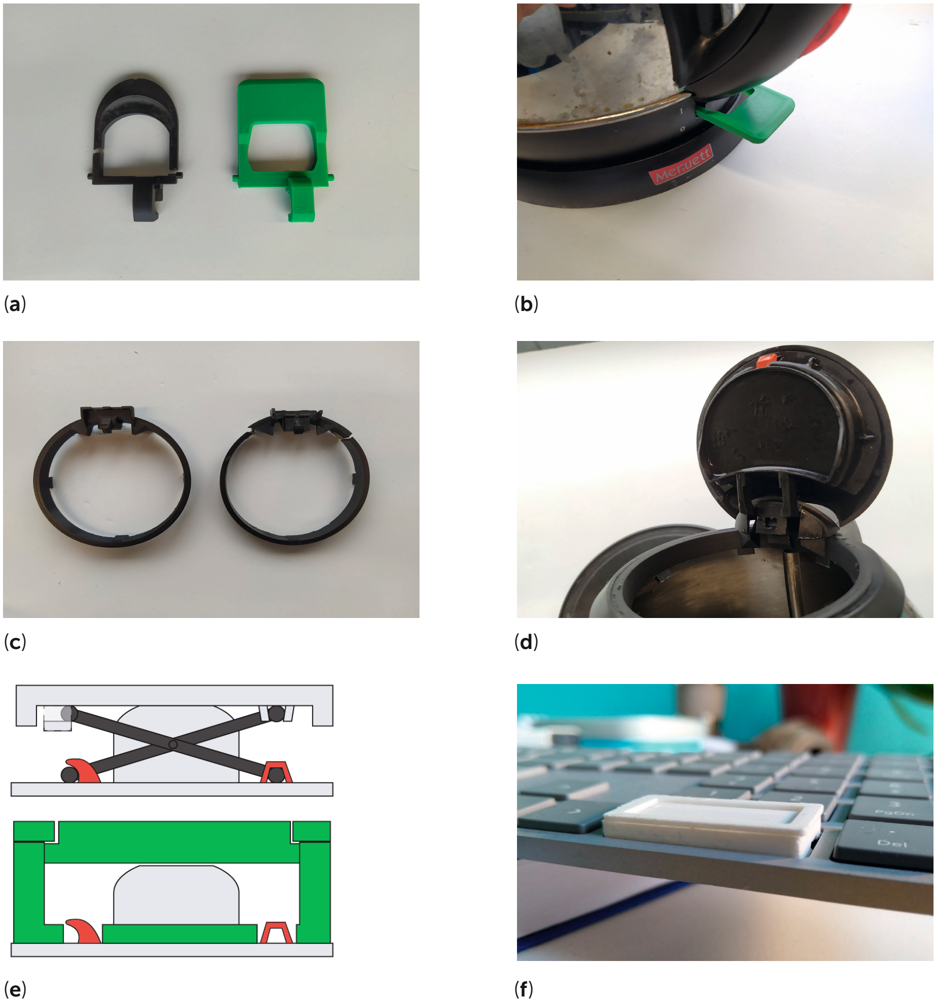


**Figure 3.2.** Comparison of the original and 3D-printed case study parts: (a) original kettle switch (left) and 3D-printed redesign (right); (b) 3D-printed kettle switch installed in kettle; (c) original kettle locking ring (left) and 3D-printed redesign (right); (d) 3D-printed kettle locking ring installed in kettle; (e) the original keyboard key scissor mechanism (above) with broken attachments (red), and the redesign (below) with 3D-printed parts (green); (f) 3D-printed parts on the keyboard.

*Process Changes*

This section describes changes that were made to the selection and order of process steps from the literature review.

The fault diagnosis steps were renamed, as the difference between fault detection, fault location, and fault isolation is not immediately clear. Therefore, we renamed these into find failure symptoms, find possible causes of failure, and diagnose repair, respectively.

Analyse part and product was split into study product architecture and study part configuration and requirements to clarify what the analysis should focus on. Product architecture, or part topology, ensures that the part fits in the product. Part configuration and requirements describes what other part properties are required to make the part function.

Test print quality was added as a process step in the experimental study. We found that a printed part could fail not only through design but also through printer inaccuracies. Injection-moulded parts have very tight tolerances, which are not always achievable with standard desktop 3D printers. Besides this, there are also commonly occurring printer failures, such as printer under-extrusion or bad build-plate adhesion. These require printer recalibration or printer setting optimisation rather than part redesign. Testing print quality will show if the error is in the design or manufacturing of the part.

Material and method selection was moved to before assess part feasibility, as the material and method have an important influence on part feasibility. We had estimated that all repair cases were feasible with FDM PLA printing, so material and method selection received little attention during the process. However, the kettle closure ring initially failed when using standard PLA. We thought the part was unsuitable for FDM printing altogether, but it did function when reprinting it with heat-resistant PLA. This shows that the chosen material and method should also be evaluated in the feasibility assessment.

*Process Validation and Clarification*

The experimental study gave more insight into part redesign and confirmed the importance of fault diagnosis, part feasibility assessment, and iteration.

Each repair case had its own redesign approach, but similar redesign techniques were applied to improve 3D printability. The redesign techniques found were strengthen (vertically printed) thin sections, simplify complex geometry, and completely redesign part topology. The first two techniques are minor adjustments and can be applied to almost all part redesigns. Completely redesign part topology, however, is a large design challenge. If this approach is required, it will signify that the part is (initially) unsuitable for 3D printing. It will then depend on the skill and determination of the user whether the repair will be successful.

Assess part feasibility was an important process step to save time and effort. The original keyboard key attachment mechanism had very tight tolerances and very thin and small geometries. The 3D printer could not handle these geometry requirements, which led to printing failures and non-functioning parts. In the end, there was insufficient design space to come to a functioning and comfortable solution. This shows that the assessment of part feasibility requires experience with 3D printing capabilities. Additionally, not all problems can be overcome through design, as there are limits to the available design space.

Iterate was still required when using the validated process steps. All three parts required iteration, mostly in the design synthesis and CAD modelling steps. The main reason for most iterations was to adjust part measurements in relation to the part topology. This was because all three parts worked with very narrow tolerances in their assembly. For the kettle locking ring, another iteration was used to optimise the material selection.

Additionally, two levels of iteration were found. Small iterations occur rapidly back and forth between steps that are closely related on a somewhat subconscious level. For example, part digitising was often interspersed with design synthesis, or printer settings were tweaked when a print failed. Big iterations occur on a larger timescale between dissimilar process steps and require conscious reflection. For example, going back to the design synthesis if the printed part failed the performance test.

### 3.3.2 Factors for Successful Repair

This section analyses to what extent the formalised 3DPfR framework helps self-repairers to achieve the successful repair of performance parts. It studies the influence of previous experience, process implementation, and part complexity on the repair result.

Repairs were slightly more often unsuccessful (17; 38%) than successful (15; 33%). A considerable number of repair results was unknown (13; 29%), of which five were due to printing errors. Most repairs focused on repairing the product (23; 51%), but a considerable number of repairs focused on added value in repair (18; 40%). The remaining “repairs” (4; 9%) focused on upgrading a product that was not broken.

#### 3.3.2.1 Previous Experience

Figure 3.3 shows the influence of previous experience on the repair result.

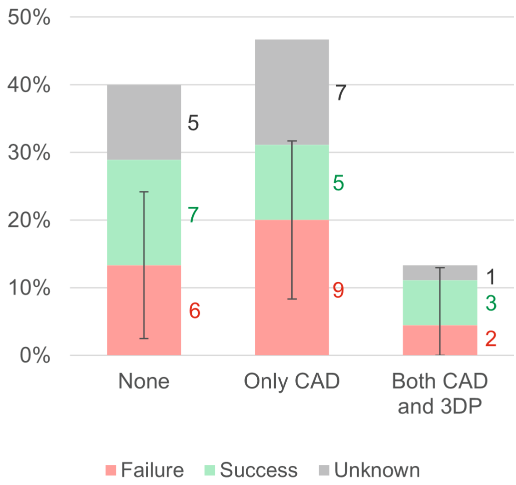


**Figure 3.3.** Repair result for each level of previous experience.

There does not seem to be a strong link between previous experience and the repair result. Participants with only CAD experience appeared slightly more likely to fail, but this is within the range of the error bars.

#### 3.3.2.2 Process Implementation

The overall process implementation studies whether participants correctly performed the 3DPfR framework steps to judge the applicability of the framework in providing guidance. Then, the process steps are detailed further per phase to find how each step influences the repair result.

*Overall Process Implementation*

Figure 3.4 shows whether each process step from the 3DPfR framework was incorrectly performed, correctly performed, or not applicable for a particular repair case. In Appendix B, a complete overview of the more granular process steps can be found.

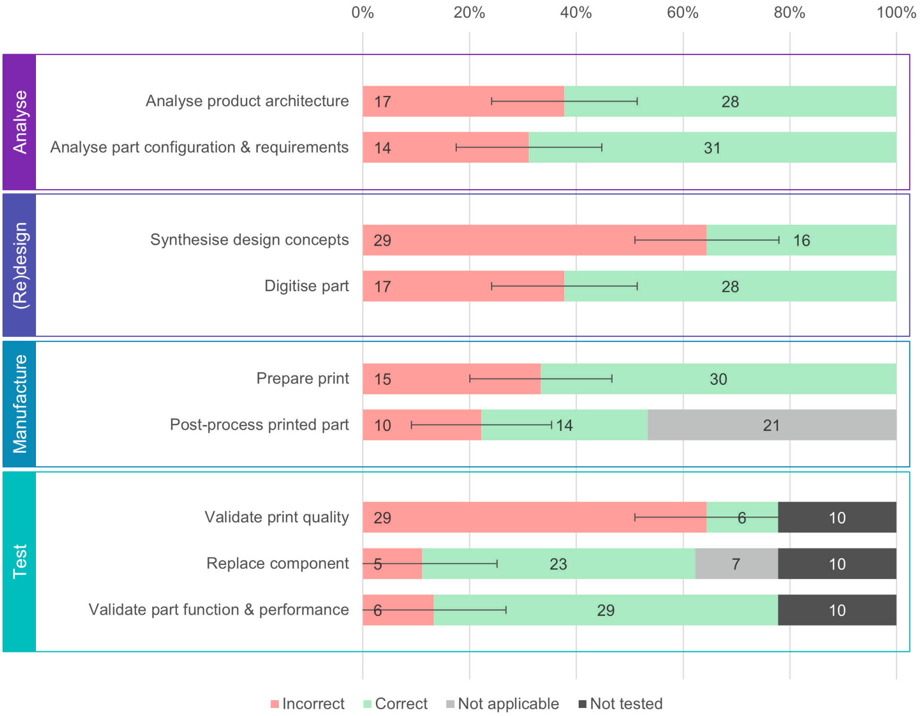


**Figure 3.4.** 3DPfR process steps (per phase) that were performed incorrectly, performed correctly, or not applicable for a particular repair case.

The most common incorrectly performed steps were test—validate print quality (29; 64%) and (re)design—synthesise design concepts (29; 64%). The most common correctly performed steps were manufacture—prepare print (30; 67%), test—validate part function and performance (29; 64%), and analyse—product architecture (28; 62%). Iterate was not part of the workshop, but 25 participants (56%) proposed iteration steps, of which 24 were estimated to be correct.

*Analyse Phase*

Figure 3.5 shows whether each analyse process step was incorrectly performed, correctly performed, or not applicable in relation to the repair result. The failed repairs are listed on the left, and the successful repairs are on the right.

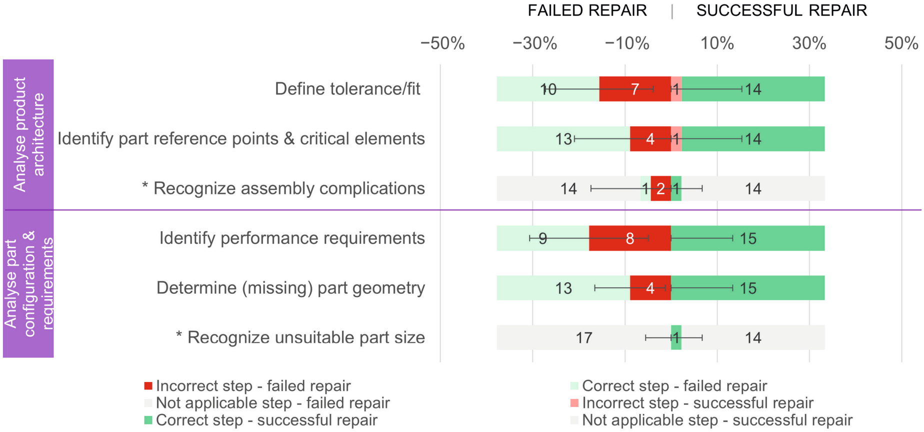


**Figure 3.5.** Effect of analysis process step correctness on the repair result. Cases with an unknown repair result have been omitted from this graph. * Process step not applicable to all repair cases.

The analyse steps define tolerance/fit and identify performance requirements have the most significant influence on the repair result. Performing these steps incorrectly has a negative influence on the repair result, as the majority of cases with incorrect steps are failed repairs. Performing these steps correctly has a slightly positive influence on the repair result, as cases are twice as likely to result in a successful repair. Similar effects can be seen for the other process steps, but they are not significant enough to make any claims.

Participants did not report on challenges in the analysis phase. Only two participants mentioned they wished they had been more attentive during the analysis. For example, “Looking back, I had to analyse the characteristics of the product a little bit further and about what their functions were. In my case, the product was not usable in the end because I ignored an important part of the original [part]”.

### *(Re)design Phase*

Figure 3.6 shows whether each (re)design process step was incorrectly performed, correctly performed, or not applicable in relation to the repair result. The failed repairs are listed on the left, and the successful repairs are on the right.

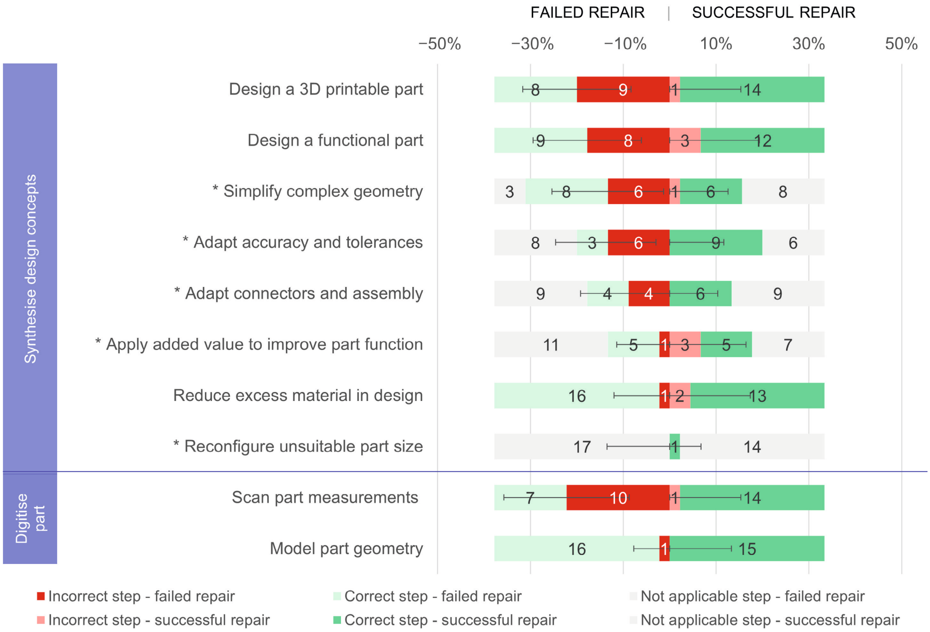


**Figure 3.6.** Effect of (re)design process step correctness on the repair result. Cases with an unknown repair result have been omitted from this graph. * Process step not applicable to all repair cases.

The design steps scan part measurements, design a 3D-printable part, and design a functional part have a negative influence on the repair result if performed incorrectly. Simplify complex geometry and adapt accuracy and tolerances seem to have a negative influence on the repair result if performed incorrectly but have smaller sample sizes. Scan part measurements and adapt accuracy and tolerances have a positive influence on the repair result if performed correctly. Model part geometry and reduce excess material in design were performed correctly by almost all participants.

Thirty participants commented on the (re)design phase, and most comments (18) concerned model part geometry in relation to previous experience. Participants without CAD experience mentioned that modelling was challenging or even stressful. For example, "It took me quite some time to figure out how the modelling works, even though I used software for beginners and the part that needed to be brought had a basic shape." However, some participants were positive about the part-modelling, even though they had no experience. They stated that using beginner CAD software Tinkercad made part-modelling easier, although less precise.

*Manufacture Phase*

Figure 3.7 shows whether each manufacture process step was incorrectly performed, correctly performed, or not applicable in relation to the repair result. The failed repairs are listed on the left, and the successful repairs are on the right.



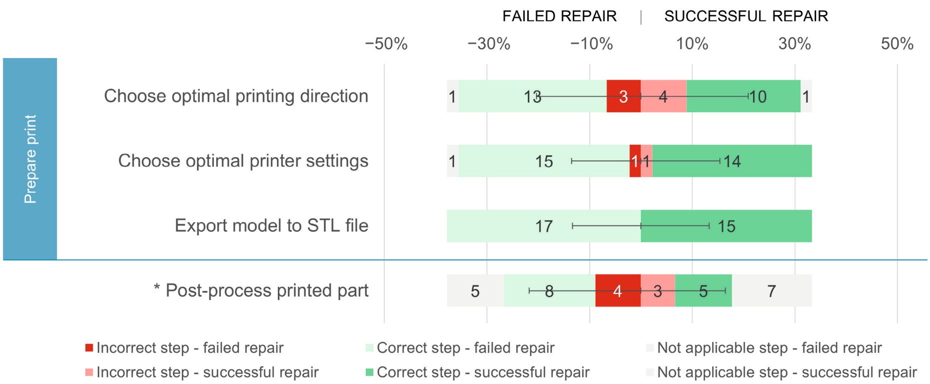


**Figure 3.7.** Effect of manufacturing process step correctness on the repair result. Cases with an unknown repair result have been omitted from this graph. * Process step not applicable to all repair cases.

The manufacturing steps choose optimal printer settings and export model to STL file were (almost) always performed correctly. Choose optimal print direction and post-process print did not seem to influence the repair result.

Twenty-seven participants commented on the manufacturing phase, of which most comments (13) were about 3D printing without previous experience. Participants stated that 3D printing was easier than expected and that the practicum made 3D printing more accessible for them. Other common remarks were about choosing the optimal printing direction in relation to post-processing (9). Removing support material was more challenging than expected, and sometimes failed due to carelessness, suboptimal placement of support material, and/or delicate designs. Participants reported they would be more considerate in choosing their printing direction next time. For example, "If I would have turned it upside down less support material would have been necessary. For a future print, I would better overthink the print orientation of my design to prevent support material at undesired places".

### 3.3.2.3 Part Complexity

The part complexity studies how factors such as part geometry completeness and part performance requirements influence the repair result. Then, an overall judgement of part suitability is made by counting the number of demanding part requirements to see how this relates to the repair result.

*Part Geometry Completeness*

Figure 3.8 shows the effect of part geometry completeness on the repair result. For a complete part, all the part geometry is known, although the part does not have to be intact. For an incomplete part, either part geometry has gone missing or has been deformed.

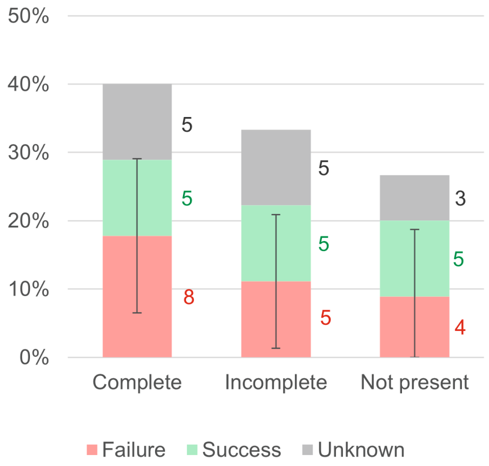


**Figure 3.8.** Effect of part geometry completeness on repair result.

There does not seem to be a link between part completeness and repair result, considering the distribution of the percentages and the extent of the error bars. A few students remarked that it was extra challenging to measure and digitise the part if it was missing. However, they were mostly able to overcome the challenge by analysing the rest of the product and how the missing part should fit in it.

*Part Requirements*

Figure 3.9 shows which part requirements were found in parts that participants selected as a repair case during the practicum.

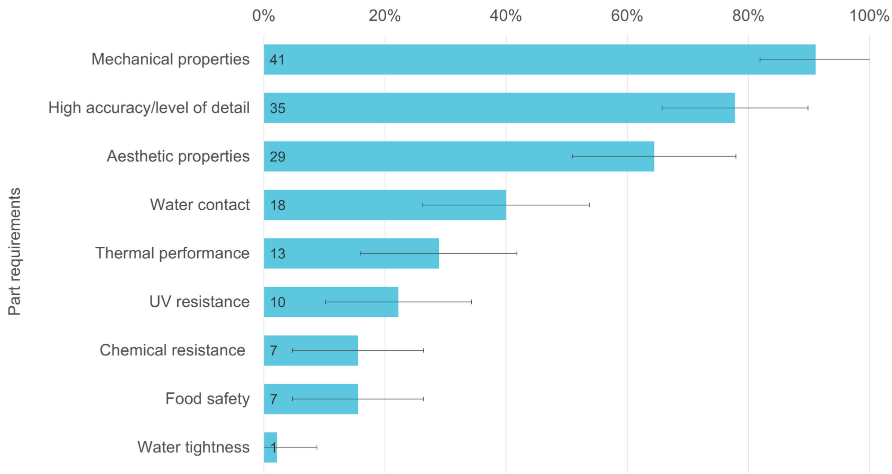


**Figure 3.9.** The types and frequency of part requirements in the parts used in this study.

The most common part requirements in our practicum study were mechanical properties (41; 91%), high accuracy/level of detail (35; 78%), and aesthetic properties (29; 64%). The least common part requirement was water tightness (1; 0%).

Figure 3.10 considers the extent of the part requirements and shows the effect of demanding part requirements on the repair result. Parts with demanding part requirements are expected to require adaptation of the part design in order to be successful. Only the demanding part requirements were considered when studying the impact of part requirements on the repair result.

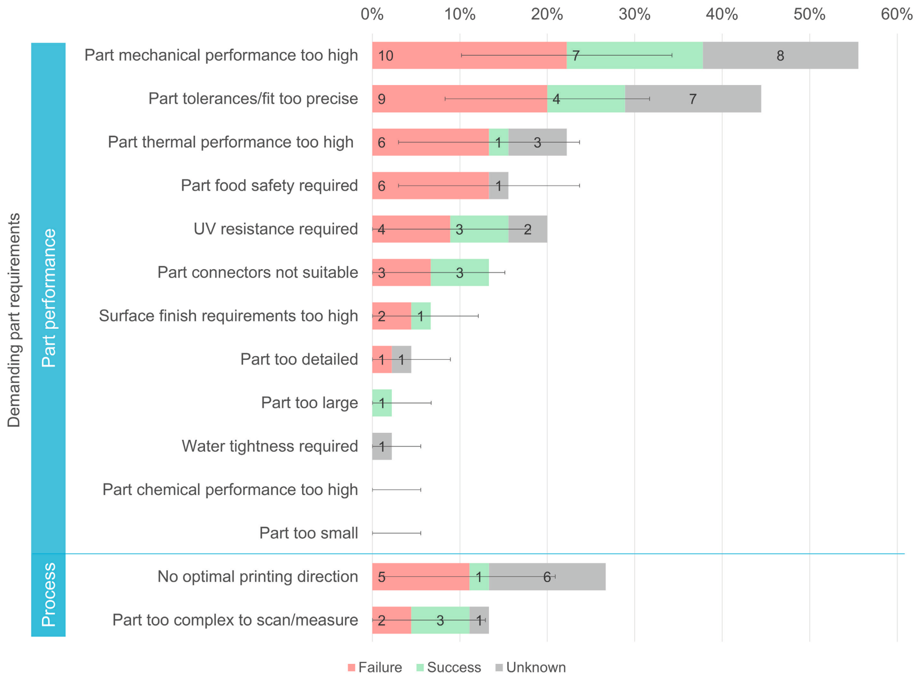


**Figure 3.10.** Effect of demanding part requirements on the repair result.

The most common demanding part requirements were part mechanical performance too high (25; 56%) and part tolerances/fit too precise (20; 44%). The least common demanding part requirements were part chemical performance too high (0; 0%) and part too small (0; 0%).

Part food safety required was never met, as it is very difficult to achieve food safety with FDM printing (Lipton et al., 2015). Additionally, if there is no optimal printing direction for the part, it is very likely that the repair will fail. Optimisation of the printing direction refers either to part performance, such as optimising mechanical strength, or the printing process, such as optimising printing time, the amount of support material, and post-processing time. This optimisation is not determined by a specific geometry feature or part requirement, but rather by the way in which geometry features and/or part requirements are combined. For all other demanding part requirements, there does not seem to be a significant effect on the repair result.

### *Overall Part Suitability*

Figure 3.11 shows the relation between overall part suitability and the repair result. Part suitability was determined using the number of unsuitable part requirements. A part was deemed unsuitable if it had over five demanding part requirements, or if (the extent of) the demanding part requirement was virtually impossible to overcome with desktop 3D printing.

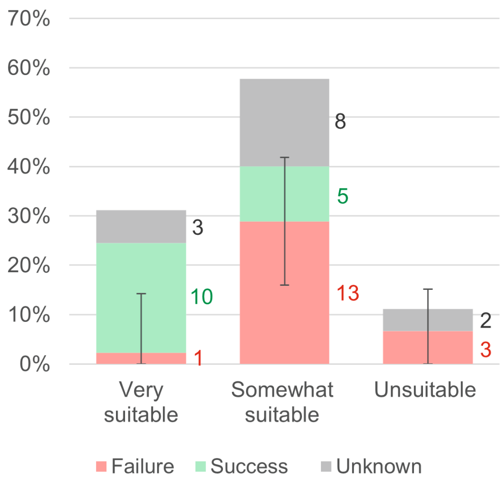


**Figure 3.11.** Effect of part suitability on the repair result.

Most parts were considered to be somewhat suitable (26; 58%), and there were very few unsuitable parts (5; 11%). Most very suitable parts were repaired successfully, but the results for somewhat suitable parts are inconclusive. The sample size for unsuitable parts is too small to draw definite conclusions, but there were no successful parts in this category.

Fourteen participants commented that part suitability played a role when selecting their repair case. For example, "I would have liked a bit more details or a more difficult object. I could not do that now because I had to figure out almost everything about 3D designing". Some participants also changed their repair case during the workshop to meet printing and modelling requirements.

## 3.4 DISCUSSION

### 3.4.1 3DPfR Framework

To generate the framework for 3DPfR, the process steps from the literature analysis and experimental design were structured further. This framework was then used to select relevant factors for further study.

#### 3.4.1.1 Finalising the Framework

Fault diagnosis was separated from the 3DPfR process as it is arguably not an iterative process phase. It is required to find the broken part and understand the part failure. This will help to prevent similar failures in the 3D-printed replacement part. However, after the fault diagnosis is complete, this phase is rarely revisited. It is even possible that the fault diagnosis is conducted before the idea of a 3D-printed replacement part arises. This also means that repair experts do not need to be design experts, as they can partner. Therefore, the fault diagnosis is still included in our framework, but not as part of the 3DPfR process.

The 3DPfR process was restructured into four phases: analysis, (re)design, manufacture, and test. These phases form a closely integrated iterative process. For example, the design decisions will determine manufacturability, while the manufacturing decisions will influence the design. A successful design might not work without the right print settings, such as resolution, print orientation, extrusion rate versus travel speed, and more; however, printer settings cannot fully correct a flawed design. Here, it does help for one person to have both design and AM experience, or it requires tight partnerships. In the experimental study, process iteration mostly took place in the design phase, such as adjusting part measurements or reiterating the design synthesis.

By restructuring the literature process steps, as described above, we came to the final iteration of the 3D printing for repair framework as shown in Figure 3.12.

A successful process depends not only on process implementation, but also on previous experience, part characteristics, the (available) printing method, equipment and materials, and time spent. Analysing the relation between these factors and the repair result will show what the most likely failure points are. Most of these factors are addressed in RQ2. Fault diagnosis was not explored further as it is not closely integrated into the 3DPfR process. The steps select method and material, print part, and iterate were not explored further due to time and equipment constraints; see Section 3.4.3, Limitations and Recommendations.

#### 3.4.1.2 Complications in Framework Application

It is not realistic to expect that a 3D-printed replacement part is a perfect replica of the original part. Assessing whether the 3D-printed part is sufficient will require a certain skill and familiarity with 3D printing and product repair. More insight into the possibilities and limitations of 3D printing for repair will be needed to better frame the scope for 3D-printable spare parts.

Additionally, the number of iterations needed to make a successful part could be a limiting factor for the implementation of 3D-printed spare parts. It is good to be familiar with 3D printing capabilities during the analysis and design process. Not everyone with a broken product will be willing to spend the needed time and effort on this process, especially if it is for low-cost appliances that are easy and affordable to replace. A way around this could be to have a database of spare parts in place, either set up by volunteers or by original equipment manufacturers.

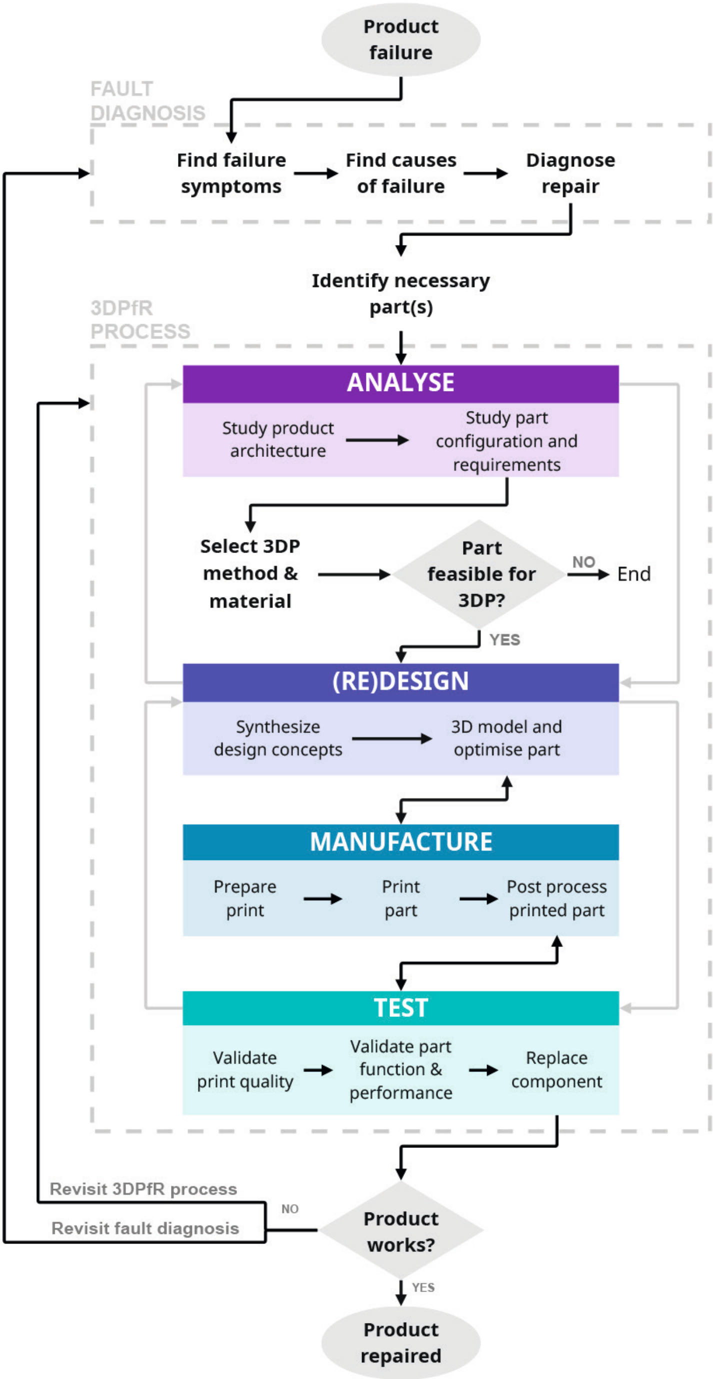


**Figure 3.12.** 3DPfR framework.

### 3.4.2 Factors for Successful Repair

The second research question focused on finding the influence of previous experience, process implementation, and part complexity on the overall repair success.

The success rate of 3D-printed spare parts is inconclusive due to the number of unknown cases. However, there are enough successful cases in this study to be able to conclude that 3D printing spare parts is an interesting opportunity to improve repair success rates. Additionally, there were numerous cases of value-added repair, which shows that improving products through 3DPfR is also an accessible concept for novice users. This opens up possibilities for product life extension through upgrading and personalisation with a 3D-printed part.

When there are multiple errors in process steps or multiple unsuitable part requirements, it is difficult to determine causal links between process implementation or part complexity and the repair result. This is due to the extended number of factors discussed and the interrelations between them. Cases with one error or fewer were all successful. However, most successful repairs still had one or more process step errors but succeeded despite them because these steps were either less critical in the process, or not erroneous to such an extent that they caused the repair to fail. All failed repair cases had multiple incorrect process steps. Additionally, only 11 out of 45 parts had one or fewer unsuitability types. The sample size is too small for the credible statistical determination of which process errors or part unsuitability types individually drive failure the most. However, the determination of which process errors and part unsuitability types are most commonly correlated with failure gives repairers a list of common problems to check in their own work.

#### 3.4.2.1 Previous Experience

There is not a clear link between previous experience and repair results. The only effect that could be seen is that people with only CAD experience were slightly more likely to fail. This could be because all the unsuitable parts were from participants with this experience level.

It could be possible that the repair result is linked to other factors than experience, such as design ideation. However, the limited number of participants with 3D printing experience limits the sample size, making the data insufficient to draw a firm conclusion. Experience in Three-dimensional printing could be helpful when designing the part, as it helps to understand what is feasible to be 3D printed. Additionally, it could be that the influence of previous experience becomes more prominent when more iterations are attempted. Then again, it can be expected that the audience of repair cafes is similarly limited in their experience. Therefore, it is promising to see that successful repairs are also possible without previous experience.

#### 3.4.2.2 Process Implementation

The most challenging 3DPfR phase is the (re)design phase, as synthesise design concepts and digitise part were often performed incorrectly. Within these steps, participants mainly failed to scan part measurements, design a 3D-printable part, and design a functional part. Model part geometry, however, was mostly performed correctly. This strengthens the assumption that a successful process depends more strongly on design decisions and less on the execution of this design through CAD. However, it should be kept in mind that the results were obtained with university-level students. Research within a wider population would be needed to test this assumption for different skill levels.



Future guidance should focus on scan part measurements, define tolerance/fit, identify performance requirements, and adapt accuracy and tolerances. The incorrect performance of these steps correlates the strongest with a failed repair result. Scan part measurements and adapt accuracy and tolerances, if performed correctly, had a relatively strong positive correlation with a successful repair result. This indicates that these are the key steps in creating a successful 3D-printed replacement part.

Interestingly, choose optimal printing direction and post-process print did not have a negative correlation with the repair result when performed incorrectly. The printing direction is especially interesting, as the printing direction seems relevant when studying part complexity. However, as stated before, the optimal printing direction can refer either to the part performance or the printing process and post-processing. It is likely that optimisation for the printing process is less crucial than the optimisation for part performance. This makes it difficult to determine the criticality of choosing the optimal printing direction and its effect on the repair success. For post-processing, all errors damaged the part integrity while removing support material, but not always in such a way that part performance was hindered. Even though these steps seem less crucial, they are still needed to perform a successful repair. Therefore, they cannot be removed from the framework.

#### 3.4.2.3 Part Complexity

Part complexity studied the effect of part completeness and part suitability on the repair result. Contradictory to the literature and expectations, part completeness did not seem to have a correlation with the repair result. However, participants remarked that it did cost more effort to reconstruct the part. This could be discouraging for users when performing DIY repair, especially for users without a technical background. Therefore, future guidance should show users that it is possible to recreate missing parts, and how to do this.

The results for unsuitable part requirements and part suitability were inconclusive. Most unsuitable part requirements did not have a significant negative correlation with the repair result. It may be that part suitability is more related to the severity of the requirement rather than the type. Related to this, it is likely that the part selection in this study is more biased towards suitability than a random selection of repair cases in a repair cafe. Participants selected parts that they thought would suit their limited experience level and expectations and even changed their selected part during the workshop. This is also reflected in the fact that there were only very few unsuitable parts in this study. More study is needed to find the limits of 3D-printed parts in relation to their performance requirements.

The only unsuitable part requirement with a more significant negative correlation with a failed repair was no optimal printing direction. It could be that, here, the optimal printing direction relates to part performance rather than the printing process. When the original part design does not have an ideal printing direction, more attention needs to be paid to the redesign phase to overcome this problem and realise a 3D-printable part design. This also illustrates the importance of the correct execution of the process steps and making the right design decisions.

### 3.4.3 Limitations and Recommendations for Future Research

This study was limited by several factors, which should be kept in mind when building upon this work.

The framework was built to be generally applicable to all printing methods, but the verification of the framework and finding factors for successful repair was performed using only FDM PLA printing. Further testing of the framework and process steps with other printing methods and materials is recommended to verify its applicability. Using other printing methods might shift the importance of certain process steps or introduce new steps. However, the problems highlighted in this current study can be expected to be relevant issues or at least relevant starting points for applying other printing methods in the context of 3DPfR.

The practicum in this study had to adapt last minute to an online environment due to COVID-19 regulation changes. This meant we were unable to use preselected repair cases, which could have affected the results for RQ2. As mentioned before, participants selected their part based on the assumed feasibility of modelling and printing. People actually repairing products do not get to make that choice. Therefore, part complexity insights should be used to inspire future research and not to draw conclusions. The online environment also meant participants could not print themselves, and not all participants were able to pick up their printed parts for testing. This resulted in limited manufacturing insights and a higher number of unknown repair result cases.

The practicum participants were students from a technical background with an affinity for sustainability. This means that participants might have been more adept than average repairers at adopting new skills such as CAD modelling. Additionally, completing the practicum was mandatory, which might have helped participants in overcoming hesitations or insecurities. In a real repair scenario, it could be that users do not start or complete the process because of the required time, effort, and skills.

The three-day practicum was limited in time, limited to printing PLA plastic with FDM machines, and limited in the number of printers available. Only one iteration could be designed and printed, and there was no time to accommodate printing errors (e.g., filament running out). Prints were grouped due to the limited number of printers, which meant some printer settings had to be adjusted. However, these factors could also be limiting factors in repair environments such as repair cafes.



This study has presented insights into process implementation and knowledge gaps in part complexity. Even though this study describes correlation instead of causality between different factors and the repair success, it can still provide repairers with a list of common problems to check and can provide researchers with a list of problems to develop solutions for. The redesign steps were found to be the most likely failure points. As there is still little guidance on redesigning existing parts for 3D printing, we recommend that further research and development should mostly be focused on these steps. Moreover, more insight is needed into what determines the suitability of parts likely to succeed in successful 3D printing. This should be conducted by considering the limits of the part requirements in more detail as well as the implementation of the process steps. Further insight into this topic could help in improving the definition and estimation of part suitability. The framework can be used to structure and find other research gaps in 3D printing for repair. Recognising and studying these gaps will help to further develop this framework and to structure future research and guidance on this topic.

Besides this, future studies could focus on factors that contribute to a successful 3DPfR process, but which were not covered in this study. These factors could be the influence and importance of time, the number of iterations, different printing materials, or the equipment used (e.g., printer, measuring tools). Different printing methods could also be considered. As stated at the beginning of this paper, these methods might be less accessible for consumers or considered too pricey. However, this assumption could be challenged as technology advances over time. Meanwhile, using printing services could also be an option to access more advanced printing methods.

Finally, after further development, we recommend testing the framework within a repair community such as a repair cafe to further develop support and guidance materials. However, this study shows that 3DPfR is a challenging process. Some users might find that the process requires too much time and effort for too little gain. Therefore, it would also be interesting to see how this framework can be applied within an industrial setting.

## 3.5 CONCLUSION

The goal of this paper was to formalise the 3D printing for repair (3DPfR) process to provide evidence-based guidance on which steps make the process successful. A 3DPfR framework was developed, which was used to identify what process factors drive the success or failure of the overall repair.

To answer the first research question, "How can the 3DPfR process that leads to a successful repair be described?", we created a 3D printing for repair (3DPfR) framework which has two functions: to analyse and describe the process and to provide high-level guidance for the process. Our study showed that the 3DPfR process can be described as an iterative design for an additive manufacturing process that is integrated into a repair process. The 3DPfR process consists of four phases: analyse, (re)design, manufacture, and test. Fault diagnosis is used to find the broken part, but it is not an iterative part of the 3DPfR process. 3DPfR is simple in principle but quite challenging in its details, which should be addressed in future research. Compared to product design and design for additive manufacturing, the 3DPfR process is less flexible, as it needs to consider an already-existing product. The process often requires multiple iteration cycles to obtain the right part performance and fit. It is not enough to just copy the original part, as has been assumed in the earlier literature because 3D-printed parts and materials perform differently than the parts and materials they replace. The required design work and the number of iterations could be limiting factors in the adoption of 3D-printed spare parts. In the future, the 3DPfR framework can be detailed further with more experimentation and user feedback.

For the second research question, "What is the influence of previous experience, process implementation, and part complexity on the overall success of the 3DPfR process?", we found that execution of the process steps was the most important predictor for repair result; previous experience and part complexity were not significant predictors. When reviewing the effect of process steps on the repair result, we found that incorrect process steps usually resulted in a failed repair, whereas a correct step did not necessarily result in a successful repair. The most challenging step was designing a 3D-printable and functional part. This shows that it is especially important to guide users in making the right design decisions during the redesign of their part. This study also showed it is difficult to predict which parts are suitable for 3D printing. Most likely, this involves the strictness of part requirements, rather than the type of requirements. This will be the subject of a future study.

Repairing a product will almost always be the most sustainable solution. 3D printing for repair could be an accessible way to give older products without spare parts a chance at a longer product lifetime. As 3D printing is flexible and rapidly evolving, it could be the key to unlocking localised, personalised, and value-added repair. This research gives a first overview of how to create a successful 3D-printed spare part and provides directions for further research.

## 3.6 APPENDIX A

Table A1 presents the full coding table that was used during the qualitative coding for research question 2.

**Table A1.** Full coding table used to create the data set.

| Code | Options | Definition | Examples from Dataset |
|---|---|---|---|
| **Overall Repair Characterisation** | | | |
| Repair result | Failure | The manufactured part is installed but the product function is not back, or the part does not fit properly. | A 3D-printed keyboard stand clip was too small to fit in the keyboard, so it did not work. |
| | Success | The part fits and the intended part functionality is restored. | The back cover of an alarm clock was successfully replaced with a 3D-printed part. |
| | Unknown | Machine error, incomplete testing phase, or otherwise insufficient information to judge the part fit and function. | Some users could not pick up their printed parts for testing as they were abroad/in different cities; for some parts, the printer ran out of filament. |
| Repair type | Repair | The repair focuses on restoring the original function of a broken part. | A washing machine button was replaced with a 3D-printed button with the same fit and function. |
| | Added value | The repair focuses on optimising the functionality of a non-broken part, or on repurposing a broken part. | A functioning Nintendo Switch joy-con rail was redesigned to make the controller more comfortable to hold. |
| | Both | The repair focuses on restoring the function of a broken part and on optimising/adding functionality/personalising the part compared to its original function. | A broken multimeter stand was replaced, and holes were added to the design to hold the probe cables. |

**Table A1.** Full coding table used to create the data set. (continued)

| Code | Options | Definition | Examples from Dataset |
|---|---|---|---|
| **Previous experience** | | | |
| Previous experience | None | The participant mentions that they had not previously used CAD modelling and 3D printing, or expressed difficulty with these skills. | "… I had no prior experience with [modelling a 3D part], it was totally unfamiliar for me what I had to do" |
| | Only CAD | The participant mentions experience with CAD modelling. | "… I already had some experience with modelling … The 3D printing itself I had actually never done before" |
| | Both CAD and 3DP | The participant mentions experience with CAD modelling and 3D printing. | "… I have had the privilege to gain a lot of experience within prototyping and products design also based on FDM 3D printing …" |
| **Process implementation** | | | |
| *Analyse process steps* | | | |
| Define tolerance/fit | Incorrect | The participant does not recognise how loose/tight the part should fit or does not pay attention to it. | One participant measured the part cavity and gave the part the same measurements, while the part should have a looser fit. |
| | Correct | The participant recognises how loose/tight the part should fit. | "Assemble type:—Loose fit" for a ring to hold a toilet seat in place. |
| Identify part reference points and critical elements | Incorrect | The identification of part reference points and critical elements is incomplete and/or incorrect. | A coffee pot lid did not take into account the reference to the coffee maker nozzle, and thus the coffee would not flow through. |
| | Correct | The identification of part reference points and critical elements is complete and correct. | A faucet knob was designed to match the existing male part of the faucet knob. |

**Table A1.** Full coding table used to create the data set. (continued)

| Code | Options | Definition | Examples from Dataset |
|---|---|---|---|
| Recognise assembly complications | Incorrect | The fact that a part is difficult to assemble (either due to original design/assembly or because of 3D-printed part properties) is not recognised. | A screw thread of a cupboard leg was redesigned only because the participant could not model a screw thread, but the redesign still had the same issues (too delicate to be printed). |
| | Correct | The fact that a part is difficult to assemble (either due to original design/assembly or because of 3D-printed part properties) is recognised. | It was recognised that a 3D-printed closure hook for a panini maker could not snap into place like the original injection-moulded part did. |
| | Not applicable | There were no assembly complications. | A 3D-printed zipper pull could use the same assembly method as the original zipper pull. |
| Identify part performance requirements | Incorrect | The identified performance requirements are not logical and/or incomplete. | It was not recognised that a 3D-printed beer bottle opener would require great strength and stiffness. |
| | Correct | The identified performance requirements are logical and complete. | A monitor cable holder "needs to be flexible enough to clip around the pole". |
| Determine (missing) part geometry | Incorrect | The geometry of the part is determined incorrectly, or incorrect assumptions are made when constructing missing geometry. | It was not noticed that the walls of a lamp bracket were slanted instead of perpendicular. |
| | Correct | The geometry of the part is determined correctly, and correct assumptions are made when constructing missing geometry. | The geometry of a washing machine knob was completely reconstructed with the help of the internal geometry. |
| Recognise unsuitable part size | Incorrect | The fact that the part is too small or too large (see *part unsuitability types*) is not recognised. | *No example available.* |
| | Correct | The fact that the part is too small or too large (see *part unsuitability types*) is recognised. | It was recognised that the handle of a vacuum cleaner was too large to fit on the build plate. |
| | Not applicable | The part was a suitable size for (desktop FDM) 3D printing. | A cooking spoon handle was small enough to fit the build plate but larger than the printing resolution. |

**Table A1.** Full coding table used to create the data set. (continued)

| Code | Options | Definition | Examples from Dataset |
|---|---|---|---|
| *(Re)design process steps* | | | |
| Design a 3D-printable part | Incorrect | The part design does not meet the design rules for FDM printing by Hubs (Brockotter, 2022). | A cupboard leg could not be replaced because the designed screw mechanism could not be printed. |
| | Correct | The part design meets the design rules for FDM printing by Hubs (Brockotter, 2022). | A vacuum bag locking mechanism was redesigned into two parts so it could be 3D printed easier. |
| Design a functional part | Incorrect | The part design does not meet (or is not expected to meet) the performance requirements and function described in the analysis phase. | A bike light holder was redesigned so the lamp would not slip down the steering wheel, but the redesign still slipped down the steering wheel. |
| | Correct | The part design meets (or is expected to meet) the performance requirements and function described in the analysis phase. | A bike tire cover attachment has the right shape to clip both the luggage rack and the bike tire cover together. |
| Simplify complex geometry | Incorrect | The part simplification, if applied, hindered part printing and/or part function. | The attachment mechanism of a smartwatch bracelet was simplified, but it would not connect to the original mechanism of the watch itself. |
| | Correct | The part simplification, if applied, improved or did not hinder part printing and/or part function. | The battery cover of a mouse was redesigned to omit non-essential holes and curves. |
| | Not applicable | The part did not have any complex geometry that needed to be simplified, or it was feasible for 3D printing without simplification. | A T-shaped bike light post was simple enough to keep the original part design. |

**Table A1.** Full coding table used to create the data set. (continued)

| Code | Options | Definition | Examples from Dataset |
|---|---|---|---|
| Adapt accuracy and tolerances | Incorrect | The part accuracy and tolerances needed to be adapted to fit 3D printing accuracy and tolerances, but this was performed insufficiently or incorrectly. | "I wanted to make it slightly bigger so [it] would not be too loose. But I overestimated the diameter which now result in some after processing." |
| | Correct | The part accuracy and tolerances needed to be adapted to fit 3D printing accuracy and tolerances, and this was performed correctly. | "In order to get a snug fit, I decreased the size I actually wanted in the CAD model by 0.5mm. .. it was important that it was maybe a bit smaller than larger in order [to fit]" |
| | Not applicable | The part accuracy and tolerances were feasible for 3D printing and did not have to be adapted. | The fit of a teapot lid was loose enough that the accuracy and tolerances did not have to be adapted. |
| Adapt connectors and assembly | Incorrect | Unsuitable part connectors and assembly methods, if any, have not been adapted to make them suitable for 3D printing, or have been adapted in such a way that they negatively affect the part fit and/or function. | A complex hinge was changed into a spring, but the spring redesign would not have any flexibility, nor act as a spring. |
| | Correct | Unsuitable part connectors and assembly methods, if any, have been adapted to make them suitable for 3D printing, if needed. | A bike cover holder was designed that clamped over the cover, as the hole where the original bracket had been attached was broken beyond use. |
| | Not applicable | The part connectors and assembly were feasible for 3D printing and did not have to be adapted. | A coat hook used screw connections, which are also feasible in the 3D-printed part. |

**Table A1.** Full coding table used to create the data set. (continued)

| Code | Options | Definition | Examples from Dataset |
|---|---|---|---|
| Apply added value to improve part function | Incorrect | The added value in the design, if applied, hindered part printing and/or part function. | One participant wrote their name on their guitar knob, and the only possible printing direction to do this resulted in infill material in the knob hole, which was difficult to remove. |
| | Correct | The added value in the design, if applied, improved or did not hinder part printing and/or part function. | A teapot lid was redesigned to hold cookies. |
| | Not applicable | There was no added value applied in the redesign of the part; see repair type *repair*. | A washing machine button was replaced with a 3D-printed button with the same fit and function. |
| Reduce excess material in design | Incorrect | The same fit and function could have been achieved with less material without too much redesign effort (e.g., the part design is unnecessarily bulky). | A faucet knob was roughly 1.5 times the size of the original knob, while this is not required for either fit or function. |
| | Correct | The part design does not use more material than needed to achieve the required fit and function. | A teapot lid was simplified to a disk instead of a dome, which reduces the amount of used material. |
| Reconfigure unsuitable part size | Incorrect | An unsuitable part size (too large/too small) has not been reconfigured to make it suitable for 3D printing, or it has been reconfigured in a way that negatively affects the part fit and/or function. | *No example available.* |
| | Correct | An unsuitable part size has been reconfigured to make it suitable for 3D printing without negatively affecting the part fit and function. | The broken handle of a vacuum cleaner was repaired by a 3D-printed patch instead of replacing the whole handle. |
| | Not applicable | The part was a suitable size for (desktop FDM) 3D printing; see analysis step *recognise unsuitable part size—not applicable*. | A cooking spoon handle was small enough to fit the build plate but larger than the printing resolution. |

**Table A1.** Full coding table used to create the data set. (continued)

| Code | Options | Definition | Examples from Dataset |
|---|---|---|---|
| Scan part measurements | Incorrect | Measurement equipment is used incorrectly and/or one or more of the part measurements are incorrect. | "Measuring round parts and the small fins on the spoon is very hard with only a ruler." |
| | Correct | Measurement equipment is used correctly, and all part measurements are correct. | A roller blinds connector was carefully measured, and all measurements were noted in a sketch. |
| Model part geometry | Incorrect | The 3D CAD model of the part has different measurements and/or scale compared to the scanned part measurements. | The lid for a blender was modelled/scaled incorrectly, and measured 2 cm instead of 20 cm. |
| | Correct | The 3D CAD model has the same measurements and scale as the scanned part measurements. | A 3D-printed dough hook "fitted perfectly and feels steady". |
| *Manufacture process steps* | | | |
| Choose optimal printing direction | Incorrect | The printing direction (part printing direction) hinders the part structure/does not benefit any part section or generates unnecessary support material. | A washing machine button (rectangular) was printed standing upright, which makes it weaker and adds support material, while it could have been printed lying flat without support material. |
| | Correct | The printing direction benefits the part structure (as much as possible) and does not generate unnecessary support material. | A lid for a teapot was printed with the visible side up, so the rough surface left after post-processing would not be visible. |
| Choose optimal printer settings | Incorrect | The chosen printing settings compromise component functions or unnecessarily increase printing time and material use. | A washing machine button was printed with 100% infill, while this part does not require great strength. |
| | Correct | The chosen printing settings do not compromise component functions and do not unnecessarily increase printing time and material use. | The aeroplane model stand was printed with a "normal instead of fine profile" as it is a "fairly large part, so fine is not needed to save time". |

**Table A1.** Full coding table used to create the data set. (continued)

| Code | Options | Definition | Examples from Dataset |
|---|---|---|---|
| Export model to STL file | Incorrect | Mistakes were made when exporting the 3D CAD model to STL, e.g., holes in the mesh or other issues described by Hubs (Bournias Varotsis, 2022). | *No example available.* |
| | Correct | The 3D CAD model from the CAD modelling software was correctly exported to an STL file format. | *All cases correctly exported the model to STL.* |
| Post-process print | Incorrect | The post-processing was not fully completed, damaged the part, or affected the part's function in some way. | A shaver attachment had narrow overhanging pins, which broke when the support underneath them was removed. |
| | Correct | The post-processing was completed and did not damage/affect the part. | The brim of a cooking spoon handle was correctly removed. |
| | Not applicable | Post-processing of the part was not required. | The aeroplane model stand was printed without support, so no post-processing was required. |
| *Test process steps* | | | |
| Not tested | | The testing phase was not conducted or completed. | "Could not test the part since I was not in Delft". |
| Validate print quality | Incorrect | Printing defects (Simplify3D, 2022) that affect part fit and/or function are not noticed, and/or the printed part weight is compared to something other than the slicer estimate (comparing the weight of the printed part to the slicer estimate can help to judge printer performance. If the actual weight is a lot lower than the estimated weight, this can indicate printing problems such as under-extrusion). | A number of people compared the weight of the printed part to the original part, which does not say anything about under-extrusion and print quality. |
| | Correct | Printing defects are noted, and the printed part weight is compared to the slicer estimate. | "Right side had a printing artefact where it was thicker". |

**Table A1.** Full coding table used to create the data set. (continued)

| Code | Options | Definition | Examples from Dataset |
|---|---|---|---|
| Replace component | Incorrect | The part was not replaced in the product, or it was installed in the wrong place and/or in any other way that affected part fit and/or function. | A pineapple cutter slicer blade was installed at the wrong end of the cutter. |
| | Correct | The part was replaced at the right location in the right order with the right connectors. | The dust bag locking mechanism was installed in the right order to hold the dust bag in place. |
| | Not applicable | The part could not be replaced in the product due to other incorrect steps (e.g., incorrect measurements). | A smartwatch bracelet half could not be reassembled due to incorrect measurements and incorrect redesign of the attachment mechanism. |
| Test setup suitable | Incorrect | The test setup is not suitable to test the part as it is not similar enough to simulate use of the part. | Attaching a bike light to a candelabra and shaking it to simulate use of the bike light on a bike. |
| | Correct | The test setup tests the right part behaviour in the original setup or a correct simulation of the original product. | A 3D-printed cooking spatula connector was submerged in boiling water to test the thermal performance. |
| *Iterate (optional, added after numerous participants voluntarily gave their redesign insights)* | Incorrect | The redesign actions offered are not likely to solve the issues with the part fit and/or function. | The proposed redesign iteration for a bottle opener was to change the measurements, while it broke because the mechanical requirements were too high. |
| | Correct | The offered redesign actions are likely to solve the issues with the part fit and/or function. | The redesign for a coffee pot lid did not work because it did not connect well to the coffee maker, and the proposed redesign was to take this element into account in the next iteration. |
| | Not mentioned | No redesign insights were mentioned. | - |

**Table A1.** Full coding table used to create the data set. (continued)

| Code | Options | Definition | Examples from Dataset |
|---|---|---|---|
| **Part complexity** | | | |
| Part completeness | Complete | The original part was intact, or a broken part had no missing pieces, or geometry could be copied of identical parts. | A missing guitar tuning knob could be modelled by looking at the knobs that were still present. |
| | Incomplete | The original part had partially missing or deformed geometry. | The mounting bracket of a lamp had pieces broken off that were missing. |
| | Not present | The original part was not available. | The back cover of the alarm clock was missing. |
| *Part requirements* | | | |
| Mechanical properties (force/flexibility/ abrasion) | Yes/No | The part requires mechanical performance to fit and function, such as strength, stiffness, bending, torsion, flexibility, elasticity, and abrasion. | A (metal) bread maker dough hook required large strength and stiffness to withstand the forces applied to it while kneading the dough. |
| High accuracy/level of detail | Yes/No | The part requires a high manufacturing accuracy and/or level of detail to fit and function. | An aeroplane model stand required higher accuracy to ensure the model aeroplane clicks in tightly. |
| Aesthetic (surface quality, colour) | Yes/No | The part is visible during use, and/or requires aesthetic properties to fit and function (e.g., smooth surface required). | The aesthetic of a desk lamp was the reason to repair it, so the 3D-printed part should not interfere with this aesthetic. |
| Water contact | Yes/No | The part requires the ability to withstand water contact in order to fit and function. | A bike light holder comes into contact with water if the bike stands outside when it rains. |
| Thermal performance | Yes/No | The part needs to withstand a certain temperature to fit and function. | A teapot lid comes into contact with hot steam. |

**Table A1.** Full coding table used to create the data set. (continued)

| Code | Options | Definition | Examples from Dataset |
| --- | --- | --- | --- |
| UV resistance | Yes/No | The part is used in a place where it is exposed to sunlight (e.g., behind a window, outside, in a car). | A bike light holder comes into contact with UV light as bikes are used outside in the sun. |
| Chemical resistance | Yes/No | The part needs to withstand certain chemicals in order to fit and function. | A toilet seat part comes into contact with the chemicals used in household cleaning agents. |
| Food safety | Yes/No | The part comes into contact with food. | A teapot lid comes into contact with the tea while pouring the tea. |
| Water tightness | Yes/No | The part needs to hold water without leaking for a longer time period. | A blender lid needs to be watertight so the blender contents do not seep through the lid. |
| *Part unsuitability types* | | | |
| Part mechanical performance too high | Yes/No | The required mechanical performance (e.g., strength, stiffness, bending, torsion, flexibility, elasticity, abrasion) is too high to be feasible with (desktop FDM) 3D printing. | The forces on the dough hook of a bread maker are very likely to be too high to replicate with 3D printing. |
| Part tolerances/fit too precise | Yes/No | The required part tolerance/fit is too high to be feasible with (desktop FDM) 3D printing. | The precision required for the attachment mechanism of a smartwatch bracelet is too high to replicate with 3D printing. |
| Part thermal performance too high | Yes/No | The required part temperature is higher than the service temperature of the used material; in this case, standard PLA. | The heat of the steam in the teapot is too hot for the teapot lid, which will likely soften and maybe deform over time. |
| Part food safety required | Yes/No | The part comes into contact with food. | A cooking spatula connector that connects the handle and spoon is likely to come into contact with the contents of the cooking pot. |

**Table A1.** Full coding table used to create the data set. (continued)

| Code | Options | Definition | Examples from Dataset |
| --- | --- | --- | --- |
| UV resistance required | Yes/No | The part is mostly used in a place where it is exposed to sunlight (e.g., behind a window, outside, in a car). | A bike light holder comes into contact with UV light as bikes are used outside in the sun. |
| Part chemical performance too high | Yes/No | The part needs to withstand chemical compounds that the used material, in this case, standard PLA, cannot withstand, e.g., antifreeze, acetone, strong acids (Prusa Polymers Team, 2021). | *PLA is likely to withstand all the (common household) chemical compounds that the case study parts will encounter* (Prusa Polymers Team, 2021). |
| Part connectors not suitable (Even though part connector requirements rely on other part requirements (e.g., snap fits require flexibility), it was chosen to make this a different requirement as it is (almost always) located locally and only required during assembly (not during normal use)) | Yes/No | The part connectors require properties that are difficult to achieve with 3D printing, e.g., snap fits or screw thread. | The back plate of an alarm clock requires a click mechanism that needs to flex considerably, which will be challenging to achieve with 3D printing. |
| Surface finish requirements too high | Yes/No | A very smooth surface is required for the part to fit and function correctly. | The lid of a coffee pot requires a smooth surface on both sides. This is difficult to achieve, as one side needs support, which leaves a rough surface. |
| Part too detailed | Yes/No | The part requires geometry that cannot be 3D printed as it is too thin/small/etc. (Brockotter, 2022). | A shaver attachment requires very small and thin prongs, which are likely to fail during printing/post-processing. |

**Table A1.** Full coding table used to create the data set. (continued)

| Code | Options | Definition | Examples from Dataset |
|---|---|---|---|
| Part too large | Yes/No | The part was larger than the average build plate of desktop FDM printers (200x200x200). | The handle of the vacuum cleaner was larger than the print bed. |
| Part too small | Yes/No | The part dimensions for functional elements were smaller than the average printing accuracy ($\pm$ 0.3 mm). | *No example available.* |
| Water tightness required | Yes/No | The part needs to hold water without leaking for a longer time period. | A blender lid needs to be watertight, so the blender contents do not seep through the lid. |
| No optimal printing direction | Yes/No | There is no printing direction that does not negatively affect the part fit, part function, printing time, and/or material use. | A phone stand for a bike mount had perpendicular overhangs in all directions, and the printing direction with the least support weakens the main part's body strength. |

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## 3.7 APPENDIX B

Figure A1 shows the full overview of all the granulated process steps per phase.

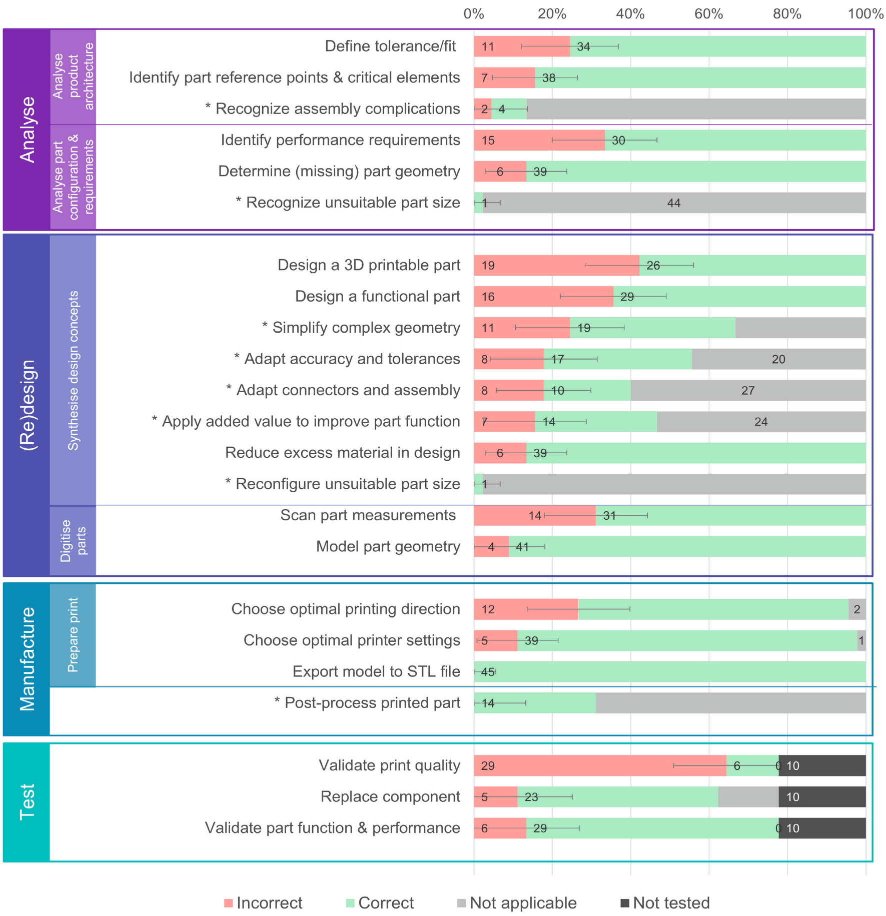



**Figure A1.** Full overview of all granulated process steps. * Process step not applicable to all repair cases.

Overall, the most common incorrect steps were:

- Test—validate print quality (29; 64%)
- (Re)design—design a 3D-printable part (19; 42%)
- (Re)design—design a functional part (16; 36%)

The most common correct steps were:

- (Re)design—export model to STL file (45; 100%)
- (Re)design—model part geometry (41; 91%)

## 3.8 REFERENCES


Agresti, A., & Coull, B. A. (1998). Approximate Is Better than " Exact " for Interval Estimation of Binomial Proportions. *The American Statistician*, *52*(2), 119–126. https://www.jstor.org/stable/2685469

Attaran, M. (2017). The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing. *Business Horizons*, *60*(5), 677–688. https://doi.org/10.1016/j.bushor.2017.05.011

Beerkens, T. (2017a). *Application of 3D printing in Repair* [Master thesis, Delft University of Technology]. http://resolver.tudelft.nl/uuid:b8842ea9-082a-4473-b181-f4c4c8a9f6f0

Beerkens, T. (2017b). *Repair Using 3D Printing : 1 Decomposition*. Instructables. https://www.instructables.com/Repair-Using-3D-Printing-1-Decomposition/

Beerkens, T. (2017c). *Repair Using 3D Printing : 3 Reproduction*. Instructables. https://www.instructables.com/Repair-Using-3D-Printing-3-Reproduction/

Bournias Varotsis, A. (2022). *Understand and fix common STL file errors*. 3D HUBS B.V. https://www.hubs.com/knowledge-base/fixing-most-common-stl-file-errors/

Brockotter, R. (2022). *Key design considerations for 3D printing*. 3D HUBS B.V. https://www.hubs.com/knowledge-base/key-design-considerations-3d-printing/

Chaudhuri, A., Gerlich, H. A., Jayaram, J., Ghadge, A., Shack, J., Brix, B. H., Hoffbeck, L. H., & Ulriksen, N. (2020). Selecting spare parts suitable for additive manufacturing: a design science approach. *Production Planning and Control*, *32*(8), 670–687. https://doi.org/10.1080/09537287.2020.1751890

Chekurov, S., Metsä-Kortelainen, S., Salmi, M., Roda, I., & Jussila, A. (2018). The perceived value of additively manufactured digital spare parts in industry: An empirical investigation. *International Journal of Production Economics*, *205*(September), 87–97. https://doi.org/10.1016/j.ijpe.2018.09.008

Chekurov, S., & Salmi, M. (2017). Additive Manufacturing in Offsite Repair of Consumer Electronics. *Physics Procedia*, *89*, 23–30. https://doi.org/10.1016/j.phpro.2017.08.009

Cooper, T. (2020). The Circular Economy in the European Union. In *The Circular Economy in the European Union*. Springer International Publishing. https://doi.org/10.1007/978-3-030-50239-3

Frandsen, C. S., Nielsen, M. M., Chaudhuri, A., Jayaram, J., & Govindan, K. (2020). In search for classification and selection of spare parts suitable for additive manufacturing: a literature review. *International Journal of Production Research*, *58*(4), 970–996. https://doi.org/10.1080/00207543.2019.1605226

Ganter, N. V., Bode, B., Gembarski, P. C., & Lachmayer, R. (2021). Method for Upgrading a Component Within Refurbishment. *Proceedings of the Design Society*, *1*(August), 2057–2066. https://doi.org/10.1017/pds.2021.467

Haruna, A., & Jiang, P. (2020). A Design for Additive Manufacturing Framework: Product Function Integration and Structure Simplification. *IFAC-PapersOnLine*, *53*(5), 77–82. https://doi.org/10.1016/j.ifacol.2021.04.127

Holmström, J., & Gutowski, T. (2017). Additive Manufacturing in Operations and Supply Chain Management: No Sustainability Benefit or Virtuous Knock-On Opportunities? *Journal of Industrial Ecology*, *21*, S21–S24. https://doi.org/10.1111/jiec.12580

Kietzmann, J., Pitt, L., & Berthon, P. (2015). Disruptions, decisions, and destinations: Enter the age of 3-D printing and additive manufacturing. *Business Horizons*, *58*(2), 209–215. https://doi.org/10.1016/j.bushor.2014.11.005

Kim, H., Cha, M., Kim, B. C., Lee, I., & Mun, D. (2019). Maintenance Framework for Repairing Partially Damaged Parts Using 3D Printing. *International Journal of Precision Engineering and Manufacturing*, *20*(8), 1451–1464. https://doi.org/10.1007/s12541-019-00132-x

Knofius, N., Van Der Heijden, M. C., & Zijm, W. H. M. (2016). Selecting parts for additive manufacturing in service logistics. *Journal of Manufacturing Technology Management*, *27*(7), 915–931. https://doi.org/10.1108/JMTM-02-2016-0025

Kunovjanek, M., Knofius, N., & Reiner, G. (2020). Additive manufacturing and supply chains–a systematic review. *Production Planning and Control*, *0*(0), 1–21. https://doi.org/10.1080/09537287.2020.1857874

Leary, M. (2020). Digital design for AM. In *Design for Additive Manufacturing*. https://doi.org/10.1016/b978-0-12-816721-2.00003-8

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

Lipton, J., Witzleben, J., Green, V., Ryan, C., & Lipson, H. (2015). Demonstrations of additive manufacturing for the hospitality industry. *3D Printing and Additive Manufacturing*, *2*(4), 204–208. https://doi.org/10.1089/3dp.2015.0031

Lorenzen, A., & Paape, A. (2018). *Leitfaden für den Einsatz 3D-gedruckter Ersatzteile in der Reparatur*. https://3d-reparatur.de/materialien-und-downloads/#broschuere

Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T. Q., & Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B: Engineering*, *143*(December 2017), 172–196. https://doi.org/10.1016/j.compositesb.2018.02.012

Park, M. (2015). Print to Repair: Opportunities and Constraints of 3D printing replacement parts. *PLATE: Product Lifetimes And The Environment*, 270–276. https://www.plateconference.org/print-repair-opportunities-constraints-3d-printing-replacement-parts/

Pérès, F., & Noyes, D. (2006). Envisioning e-logistics developments: Making spare parts in situ and on demand. State of the art and guidelines for future developments. *Computers in Industry*, *57*(6), 490–503. https://doi.org/10.1016/j.compind.2006.02.010

Pozo Arcos, B., Bakker, C., Flipsen, B., & Balkenende, R. (2020). Practices of fault diagnosis in household appliances: Insights for design. *Journal of Cleaner Production*, *265*, 121812. https://doi.org/10.1016/j.jclepro.2020.121812

Prusa Polymers Team. (2021). *Chemical resistance of 3D printing materials*. Prusa Polymers a.s. https://prusament.com/chemical-resistance-of-3d-printing-materials/

Roozenburg, N. F. M., & Eekels, J. (1995). *Product Design: Fundamentals and Methods*. Wiley.

Sabbaghi, M., Esmaeilian, B., Cade, W., Wiens, K., & Behdad, S. (2016). Business outcomes of product repairability: A survey-based study of consumer repair experiences. *Resources, Conservation and Recycling*, *109*, 114–122. https://doi.org/10.1016/j.resconrec.2016.02.014

Šajn, N. (2022). *Right to Repair*. European Parliamentary Research Service. https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/698869/EPRS_BRI(2022)698869_EN.pdf

Samenjo, K., van Oudheusden, A., Bolaños, J., Flipsen, B., & Faludi, J. (2021). Opportunities For 3D-printable Spare Parts : Estimations From Historical Data. *4th PLATE Virtual Conference 2021, May.*

Sasson, A., & Johnson, J. C. (2016). The 3D printing order: variability, supercenters and supply chain reconfigurations. *International Journal of Physical Distribution and Logistics Management*, *46*(1), 82–94. https://doi.org/10.1108/IJPDLM-10-2015-0257

Sauerwein, M., Bakker, C., & Balkenende, R. (2018). Annotated Portfolios as a Method to Analyse Interviews. *DRS2018: Catalyst*, *3*, 25–28. https://doi.org/10.21606/drs.2018.510

Sauerwein, M., Doubrovski, E., Balkenende, R., & Bakker, C. (2019). Exploring the potential of additive manufacturing for product design in a circular economy. *Journal of Cleaner Production*, *226*, 1138–1149. https://doi.org/10.1016/j.jclepro.2019.04.108

Scott, K. A., & Weaver, S. T. (2014). To Repair or Not to Repair: What is the Motivation? *Journal of Research for Consumers*, *January 2014*, 1–31.

Simplify3D. (2022). *Print Quality Troubleshooting Guide*. Simplify3D. https://www.simplify3d.com/support/print-quality-troubleshooting/

Svensson-Hoglund, S., Richter, J. L., Maitre-Ekern, E., Russell, J. D., Pihlajarinne, T., & Dalhammar, C. (2021). Barriers, enablers and market governance: A review of the policy landscape for repair of consumer electronics in the EU and the U.S. *Journal of Cleaner Production*, *288*. https://doi.org/10.1016/j.jclepro.2020.125488

Terzioğlu, N., Brass, C., & Lockton, D. (2016). 3D Printing for Repair : A Paradigm Shift in Fixing Our Relationships with Things. *Sustainable Innovation*, *November*(21st international conference), 274–281.

Terzioğlu, N., & Wever, R. (2021). Integrating repair into product design education: Insights on repair, design and sustainability. *Sustainability (Switzerland)*, *13*(18). https://doi.org/10.3390/su131810067

Vaneker, T., Bernard, A., Moroni, G., Gibson, I., & Zhang, Y. (2020). Design for additive manufacturing: Framework and methodology. *CIRP Annals*, *69*(2), 578–599. https://doi.org/10.1016/j.cirp.2020.05.006

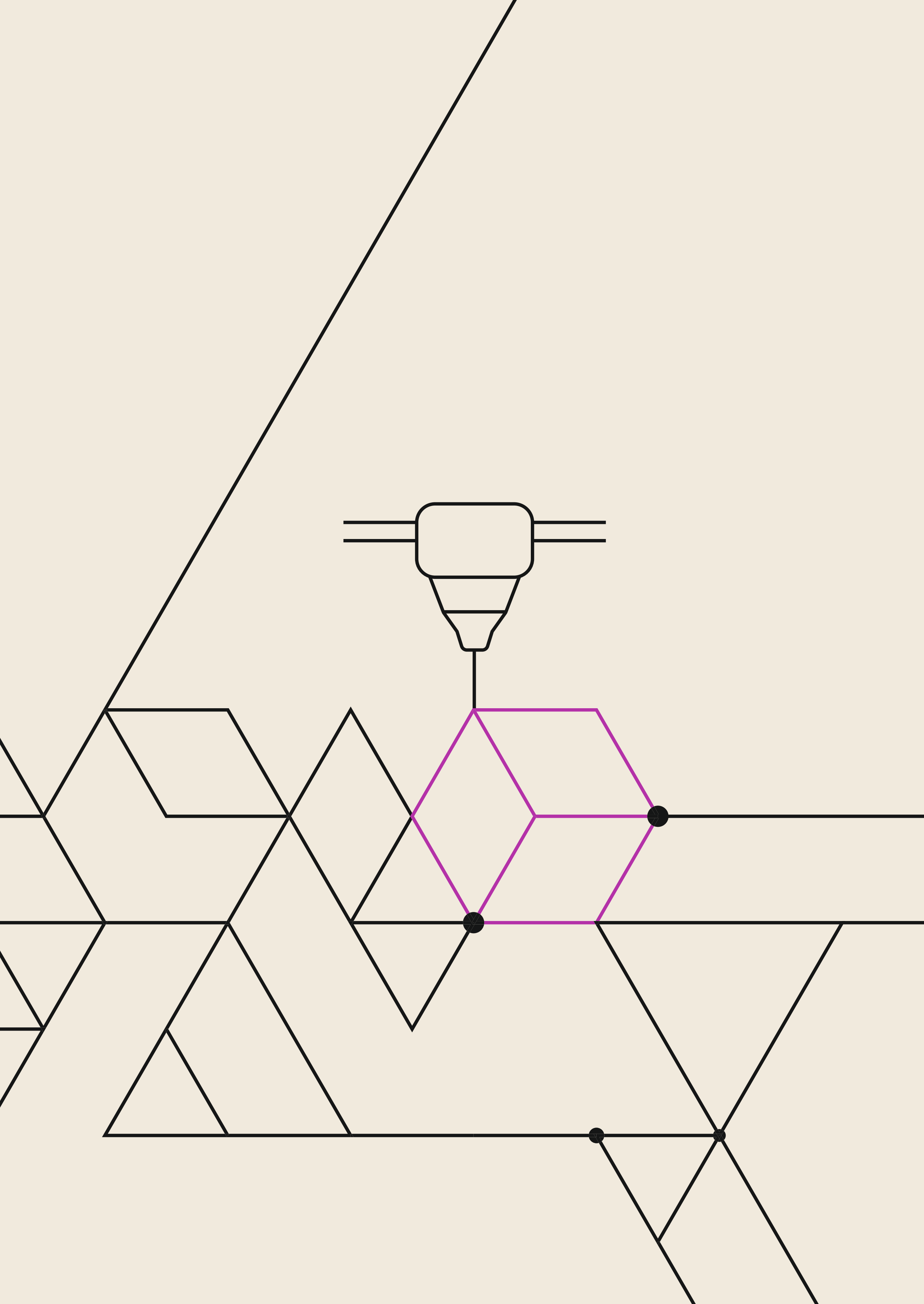
Westerweel, B., Basten, R. J. I., & van Houtum, G. J. (2018). Traditional or Additive Manufacturing? Assessing Component Design Options through Lifecycle Cost Analysis. *European Journal of Operational Research*, *270*(2), 570–585. https://doi.org/10.1016/j.ejor.2018.04.015

Wiberg, A., Persson, J., & Ölvander, J. (2019). Design for additive manufacturing – a review of available design methods and software. *Rapid Prototyping Journal*, *25*(6), 1080–1094. https://doi.org/10.1108/RPJ-10-2018-0262

Yang, L., Hsu, K., Baughman, B., Godfrey, D., Francisco Medina, M. M., & Wiener, S. (2017). Design for additive manufacturing. In *Additive Manufacturing of Metals: The Technology, Materials, Design and Production* (1st ed., pp. 81–160). Springer International Publishing AG. https://doi.org/https://doi-org.tudelft.idm.oclc.org/10.1007/978-3-319-55128-9

Yang, S., Tang, Y., & Zhao, Y. F. (2015). A new part consolidation method to embrace the design freedom of additive manufacturing. *Journal of Manufacturing Processes*, *20*(February 2016), 444–449. https://doi.org/10.1016/j.jmapro.2015.06.024

Zijm, H., Knofius, N., & van der Heijden, M. (2019). Additive Manufacturing and Its Impact on the Supply Chain. In *Operations, Logistics and Supply Chain Management* (pp. 521–543). https://doi.org/10.1007/978-3-319-92447-2_23



CHAPTER 4

# Feasibility of On-demand Additive Manufacturing of Spare Parts

This chapter was originally published as van Oudheusden, A.; Buijserd, A.; Doubrovski, Z.; Flipsen, B. Feasibility of On-Demand Additive Manufacturing of Spare Parts. In *PLATE 2023: 5th PLATE Conference*; Aalto University: Espoo, Finland, 2023; pp. 1129–1136.

## ABSTRACT

Spare parts availability is crucial for extending the life of consumer products. However, long-term availability could lead to high stocks of spare parts, which might not be used. Instead, on-demand manufacturing of spare parts with additive manufacturing (AM) is a promising alternative. This paper presents a method to evaluate parts on their eligibility for AM spare parts. The parts evaluation is based on AM technology accessibility as well as part requirements. This method was tested by assessing all parts of the Dyson V11 broom-stick vacuum-cleaner and validated by printing and testing a selection of parts. For this, both plastic and metal spare parts were made through fused deposition modelling (FDM), stereolithography (SLA), binder jetting (BJ), material jetting (MJ), selective laser melting (SLM), selective laser sintering (SLS), and multi jet fusion (MJF), using both desktop FDM printers and off-site service providers. Based on these results, we conclude that currently only a small number of parts can be replaced by additive manufactured parts without considerable redesign efforts. AM parts can compete on price with the current stocked parts, but may be more expensive for other products. We also identified additional functional requirements for evaluating the eligibility of a spare part for AM.

## 4.1 INTRODUCTION

The 2014 EU circular economy strategy considers maintenance and repair important ways of preserving resources and prolonging consumer products' lifespan (Šajn, 2019). To conduct repairs, access to spare parts, tools, and information is required, which are often controlled by the original equipment manufacturer (OEM) of the product (Svensson-Hoglund et al., 2021). The spare parts inventory is normally held by an OEM or third-party service provider to fulfil warranties (Zhang, Huang, & Yuan, 2021). This means that consumers can only repair their products for a short time (typically 2 years) and only through the OEM service (Hernandez & Miranda, 2020). Spare parts may not be available when the production of the products ceases (Zhang, Huang, & Yuan, 2021). Instead, it can become more cost effective for OEMs to replace a broken product, which further affects spare part availability (Frenk et al., 2019; Van Der Heijden & Iskandar, 2013).



The 2019 EU Ecodesign regulations include reparability requirements, like increased spare part availability. Manufacturers need to ensure that specific parts are available within 15 working days for seven to ten years after the last market release (European Commission, 2019; Šajn, 2022). The European Commission is exploring the potential of implementing a repair score system based on repair, reuse, and upgrade standard EN 45554 (European Commission, 2022, p. 7).

Long-term spare part availability means that OEMs need to find cost-effective ways to keep spare parts stock for older models (Svensson-Hoglund et al., 2021). To increase spare part availability while preventing obsolete stocks, on-demand spare parts manufacturing with additive manufacturing (AM) could be used. Digital spare parts can reduce wait time, labour cost, delivery time and costs, emissions, material waste, and inventory (Attaran, 2017; Chekurov et al., 2018). Additionally, AM economics make it ideal for on-demand spare parts manufacturing (Ford, Despeisse, & Viljakainen, 2015).

However, not all spare parts can be 3D printed. Recent research has established printability requirements, especially related to part geometry (Chaudhuri et al., 2020). Van Oudheusden et al. (2023) have shown that AM is less suited to facilitate self-repair due to the redesign that is often needed to make parts manufacturable with AM at a similar mechanical performance. However, AM might be suitable in professional repair. More insight is then needed on to what extent spare parts for consumer products can be replaced by spare parts made with additive manufacturing techniques. We need to be able to evaluate the printability of product parts, based on accessibility, part functionality, and economic feasibility. Thus, the research question of this paper is, "How can we evaluate the printability of product parts based on part requirements?"

To answer these questions, we studied the accessibility of AM methods by looking at which methods are widely available, affordable, and of high enough quality, while considering both direct ownership and printing services. Then, we constructed a list of part requirements and used these in a theoretical assessment of all the parts in a household appliance. This theoretical assessment was then validated through printing and testing a selection of parts.

## 4.2 METHOD

Part printability was evaluated for a high-end vacuum cleaner Dyson V11 Torque Drive (about € 650-€700). The Dyson V11 was selected as it is an advanced household appliance offering a multitude of complex parts made from different materials. As such, it is considered an interesting case study.

The vacuum cleaner was fully disassembled using commonly available tools: PH1 (Philips) screwdriver, T8 (Torx) screwdriver, plastic prying tools, needle nose pliers, cutting pliers, flat screwdrivers, and hammer. The hammer and flat screwdrivers were used together to remove smaller parts which could only be removed with considerable force (e.g., the smaller roller wheel axles in the brush head).

The parts were mapped using the Product Breakdown Structure (PBS) method (NASA, 2016). The PBS was complemented with the part material, if identified. For further distinction, parts were only considered "eligible" for additive manufacturing if they were not standardized or commonly available parts, such as fasteners, springs, or bearings. These could likely be purchased faster, more affordably, and at higher quality than they could be printed. Parts that could not be fully disassembled were also not considered eligible. The resulting eligible selection of spare parts would need to be printable through AM.

For assessing part printability, printing methods were considered that are commonly available through service providers: fused deposition modelling (FDM), stereolithography (SLA), binder jetting (BJ), material jetting (MJ), selective laser melting (SLM), selective laser sintering (SLS), and multi jet fusion (MJF).

Printability of parts was assessed on the following eight limiting criteria, as defined by van Oudheusden et al. (2023): (1) exposure to high forces, (2) exposure to high temperatures, (3) accurate fit required, (4) fine details, (5) smooth surface or low friction required, (6) complex curvatures, (7) complex geometries, and (8) complex or inaccessible cavities. Guidelines were defined for each criterion to increase the scoring reproducibility, see Buijserd (2022). Criteria were only marked as applicable if they were essential for part functioning. For example, if a part had complex cavities required for injection moulding but without further functional purpose, the criterion did not apply. A part printability rating was calculated for each part by starting with a score of nine and subtracting one point for each applicable limiting criterion. A part failing all eight limiting criteria scores a 1. A low printability score means a part will be more difficult to print and that careful consideration is needed of the printing method, printing material, and printer settings.

Printed part affordability was evaluated by making three roughly modelled “mock-up” parts. The outer part dimensions and material volumes roughly matched the original parts, but no details were modelled. These mock-ups were submitted to service providers for a price quote, which was then compared to the original spare part cost.

## 4.3 RESULTS



### 4.3.1 Parts mapping

The Dyson V11 was disassembled into 174 parts, of which 139 are unique, see Figure 4.1. The parts are grouped in 23 sub-assemblies, which in turn constitute six main part assemblies. Some subassemblies, like the rear dustbin seal, the motors, and the battery pack, could not be disassembled without breaking the parts or endangering the repairer. Excluding all non-eligible parts gave 67 eligible unique parts.

**Figure 4.1.** The disassembled Dyson V11.

Figure 4.2 shows the high-level hierarchical breakdown and the distribution of unique eligible parts over the (sub)assemblies. The brush head has the most with 26 unique eligible parts, followed by the vacuum section with 21 such parts.

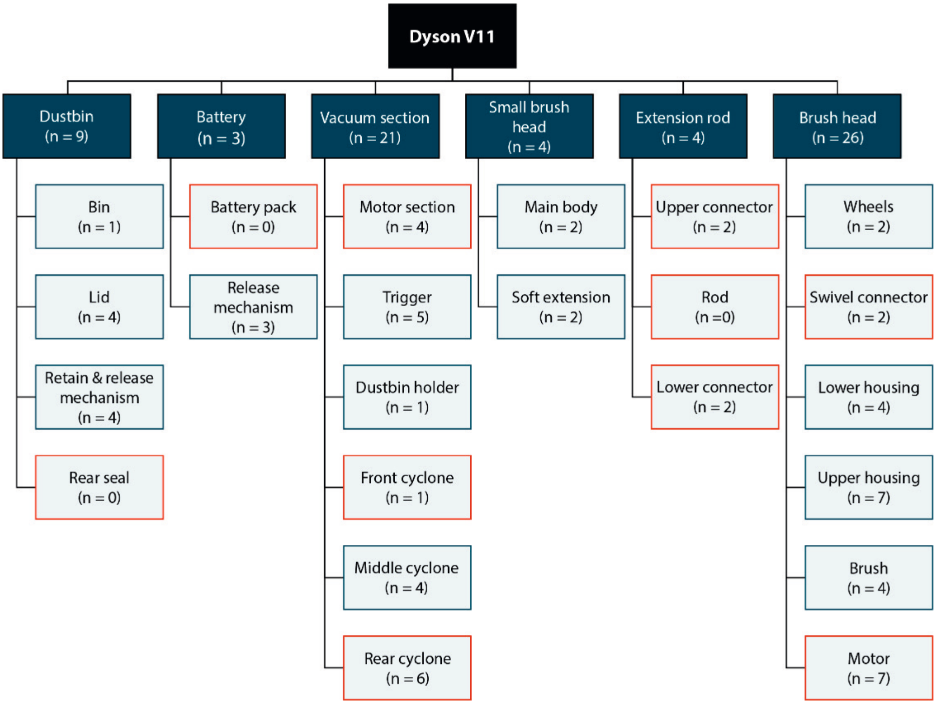



**Figure 4.2.** The Dyson V11 hierarchical breakdown. Darker boxes are assemblies, lighter boxes are subassemblies. The numbers indicate the number of eligible unique parts in each (sub)assembly. A red bevel indicates the subassembly could not be fully disassembled.

## 4.3.2 Materials

Figure 4.3 shows most parts are made of plastic, and that many different materials have been used. In total 25 different materials and material blends were identified, but for some materials the exact composition could not be defined. The multi-material group has the largest variety of materials, including nine different combinations.

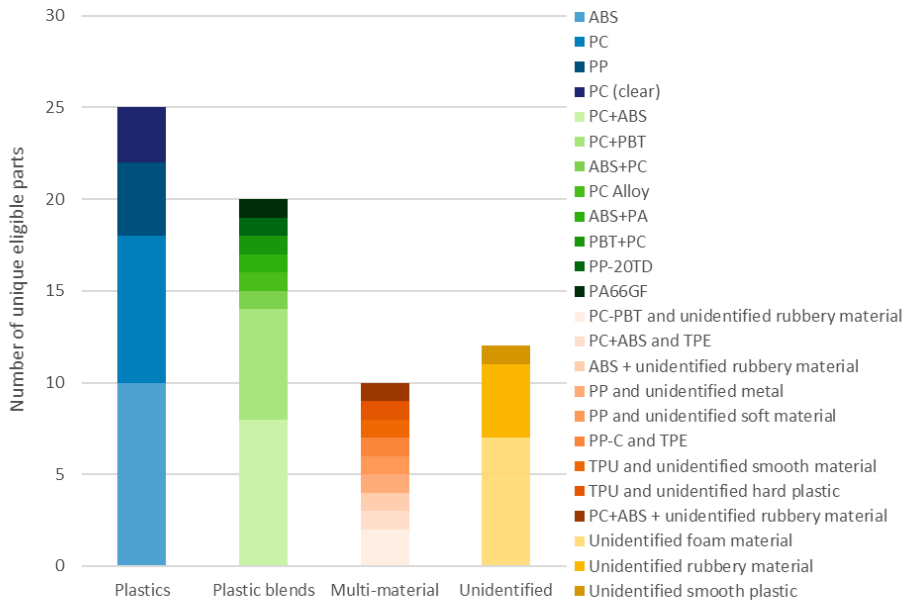



**Figure 4.3.** The material use in the Dyson V11. These materials include (blends of) acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polypropylene (PP), polybutylene terephthalate (PBT), polyamide (PA), thermoplastic elastomer (TPE), PP copolymer (PP-C), thermoplastic polyurethanes (TPU), PP reinforced with 20% talc (PP-20TD), and PA 66 with glass fibre (PA66GF).

### 4.3.3 Printability

Each part of the Dyson V11 was assessed using the eight limiting criteria mentioned in the Methods section, see for example Figure 4.4. Figure 4.5 shows the part printability scores for all eligible unique parts. Nearly all parts encounter one or more limiting criteria. Most parts encounter one limiting criterion, the lowest score was a three, and only six parts scored 9 out of 9. When assessing these high scoring parts, four of them were found to be flat foam gaskets to close part connections. These were difficult for FDM printing to match material compressibility. The other two parts could be replaced with FDM printed copies.

Still, most parts score relatively well on these criteria, and parts are usually still printable even when multiple limiting criteria apply. For example, the spring clip shown in Figure 4.4 had three limiting criteria but was printed successfully using SLS, SLM, and BJ.

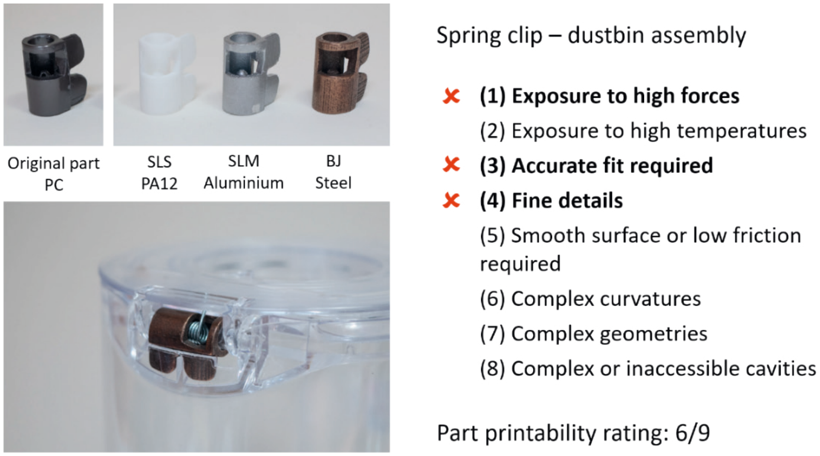



**Figure 4.4.** The spring clip printed in various materials. Limiting criteria that apply are marked with red X'es.

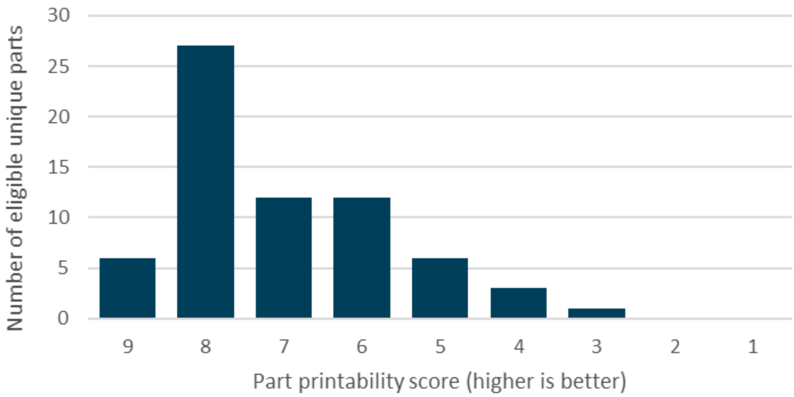



**Figure 4.5.** The Dyson V11 part printability scores.

Figure 4.6 indicates the occurrence of each limiting criterion. The main challenge is parts with fine details, which was marked applicable to 29 unique parts, but also other geometry related factors score high. The most frequent functional limiting factor was exposure to large forces during use.

When applying the limiting criteria, we further noticed that multiple parts of the Dyson V11 were made of flexible materials, such as rubber-like seals or soft-touch TPU parts. These materials can have properties like elasticity or flexibility beyond standard additive manufacturing capabilities. Additionally, there were multiple parts made of foam. This is not a common material in additive manufacturing, which can make it difficult to achieve the same compressibility. Other parts were multi-material parts, meaning that the materials of the part are irreversibly connected, such as a metal filter embedded in an injection moulded part. If the part cannot be replaced with a part printed in a single material, other strategies or specific printing methods are required, which are expected to complicate part production.

### 4.3.4 Affordability

The cost of spare parts for the Dyson V11 was assessed and compared with the costs of the printed replacement parts. Dyson offers a replacement for all Dyson V11 parts, but except for the HEPA filter, parts are not sold separately. Instead, consumers are required to buy and replace an entire (sub)assembly. For example, the lid can only be purchased as part of the dustbin reservoir (Dyson, 2023). Prices for original spare parts in this study therefore represent the cheapest option available for the part.



The cost of the printed replacement parts was evaluated by making three mock-up parts for the Dyson V11 and retrieving a price quote from a service provider. Figure 4.6 shows examples of one part. Table 4.1 compares the costs for printing three parts (lid, metal filter holder, and retainer clip) against the cost for the OEM replacement.

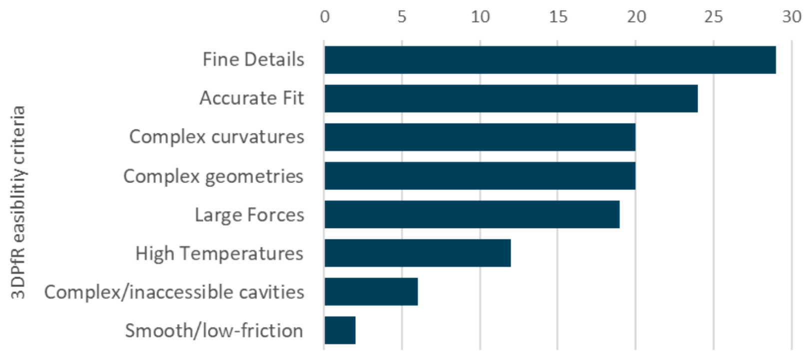



**Figure 4.6.** The occurrence of limiting criteria in the Dyson V11.

**Table 4.1.** Quoted prices for three mock-up parts of the Dyson V11. The cells marked in grey are more expensive than the OEM replacement.

| Part | Cost OEM replacement | SLS | MJF | BJT – steel | SL – grey | FDM – ABS |
|---|---|---|---|---|---|---|
| **Lid** | € 33.90 | € 19.07 | € 21.04 | *€ 152.52* | *€ 78.92* | *€ 63.70* |
| **Metal filter holder** | € 100.90 | *€ 106.27* | € 60.99 | *€ 427.65* | *€ 139.95* | € 52.50 |
| **Retainer clip** | € 40.00 | € 13.27 | € 13.53 | € 32.06 | € 32.43 | € 9.10 |

## 4.4 DISCUSSION

For this vacuum cleaner, 67 out of 139 unique parts were considered eligible for printed spare parts, even if a digital file is present and all printability-limiting criteria are overcome. Only 33 out of 139 parts scored very highly (8 or 9) in printability criteria. Multiple limiting criteria were encountered for most parts. Although the analysis only considered a single product, this product can be considered exemplary for many household appliances that use injection moulded plastic and multi-material parts, and that group parts in inaccessible (sub-)assemblies. Also, the multitude of materials used poses challenges to direct fabrication with AM as the manufacturing of such parts cannot be easily transposed. This implies that supplying spare parts through local AM requires either adaption in the product design to produce parts with both AM and conventional manufacturing, or that manufactures supply a digital file for AM that allows the printing of a functionally equivalent (but different) part.

Considering the method of establishing printability by assessing limiting criteria, Figure 4.4 shows that the criteria helped clearly distinguish between more printable and less printable parts. However, we observed that several parts were sensitive to printability issues despite a high score. This leads to additional criteria like flexibility/elasticity, compressibility, and multi-material composition (as with overmoulded parts). The highest-scoring parts were foam gaskets, which could also be produced by laser cutting sheets, so AM was not a unique enabler for their replacement.

The price of printed parts appears similar to the price of spare parts obtained through the OEM, but this is partly because the OEM requires consumers to buy a complete (sub-) module instead of just the needed part. Thus, AM spare parts are likely to be significantly more expensive than original spare parts for companies that do allow the purchase of individual spare parts. However, these economics could change for older products for which parts are rare.

Even if manufacturing AM spare parts is possible, quality guarantees will be needed. To ensure that printed spare parts are reliable, sustainable, and safe, some form of quality control and certification should be established, either through the OEM or AM service providers.

### 4.4.1 Limitations and recommendations

This study was limited by several factors. Part testing only considered the fit and short-term performance of the AM part, which makes it difficult to determine limiting criteria of long-term part performance. Also, only small parts were printed in metal, which could affect affordability for larger parts. Additionally, using an AM service provider meant that there was limited insight into the printing process, costs, and lead times. Industry can be expected to face the same challenges, but on the other hand, they can strive for more insightful collaborations.

For future research, we recommend further research into part printability to refine the current list of limiting criteria. As mentioned above, material properties like flexibility/elasticity, compressibility, and multi-material should also be considered. Additionally, research can focus on design strategies to overcome the challenges indicated by the limiting criteria. We also recommend further research to find the crossover point where AM of spare parts becomes preferable to conventional production, both environmentally and economically. To this end, we recommend that industry and OEMs focus on enabling AM of spare parts when designing the original part. Finally, additional developments in legislation and certification are needed to ensure that spare parts are safe to use.



## 4.5 CONCLUSION

Based on these results, we conclude that printed spare parts can be affordable, but that only a small selection of parts is suitable for additive manufacturing. Overall product complexity and part requirements such as fine details and accurate fit can make it difficult to reproduce parts without considerable redesign efforts. We also identified additional criteria for assessing part printability, which are elasticity and flexibility, compressibility, and multi-material. As additive manufacturing methods continue to develop and improve, it can be assumed that printed parts will become more accessible and affordable in the future.

Products should be designed for repair, and designing parts for printing on-demand can be part of this. Printing on demand means manufacturers could limit their stock of less-common parts, keep costs low, and have spare parts available long after warehoused parts would be economically prohibitive. Currently, a relatively small percentage of spare parts can be printed, but this could be fixed with redesign for printability (or if alternative printable spare parts are designed). Designing for repair is one of the many requirements to produce sustainable consumer products.

## 4.6 REFERENCES


Attaran, M. (2017). The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing. *Business Horizons*, 60(5), 677–688. https://doi.org/10.1016/j.bushor.2017.05.011

Buijserd, A. (2022). *Guidelines for Designing and Making Advanced 3D Printed Replacement Parts* [Master thesis, Delft University of Technology]. http://resolver.tudelft.nl/uuid:4d5b6e03-19e3-4b2c-8ac8-90b9b3636580

Chaudhuri, A., Gerlich, H. A., Jayaram, J., Ghadge, A., Shack, J., Brix, B. H., Hoffbeck, L. H., & Ulriksen, N. (2020). Selecting spare parts suitable for additive manufacturing: a design science approach. *Production Planning and Control, 32*(8), 670–687. https://doi.org/10.1080/09537287.2020.1751890

Chekurov, S., Metsä-Kortelainen, S., Salmi, M., Roda, I., & Jussila, A. (2018). The perceived value of additively manufactured digital spare parts in industry: An empirical investigation. *International Journal of Production Economics, 205*(September), 87–97. https://doi.org/10.1016/j.ijpe.2018.09.008

Dyson. (2023). *Reservoir Onderdeelnr. 970050-01.* https://www.dyson.nl/support/journey/spare-details.970050-01

European Commission. (2019). *The new ecodesign measures explained*. October. https://ec.europa.eu/commission/presscorner/detail/en/QANDA_19_5889

European Commission. (2022). *Ecodesign and Energy Labelling Working Plan 2022-2024*. https://energy.ec.europa.eu/ecodesign-and-energy-labelling-working-plan-2022-2024_en

Ford, S., Despeisse, M., & Viljakainen, A. (2015). Extending product life through additive manufacturing : The sustainability implications. *Global Cleaner Production and Consumption Conference*, December, 1–4. https://www.researchgate.net/publication/282075975_Extending_product_life_through_additive_manufacturing_The_sustainability_implications

Frenk, J. B. G., Javadi, S., Pourakbar, M., & Sezer, S. O. (2019). An exact static solution approach for the service parts end-of-life inventory problem. *European Journal of Operational Research, 272*(2), 496–504. https://doi.org/10.1016/j.ejor.2018.06.041

Hernandez, R. J., & Miranda, C. (2020). *Empowering Sustainable Consumption by Giving Back to Consumers the 'Right to Repair.'* 1–15.

NASA. (2016). *Expanded Guidance for NASA Systems Engineering: Crosscuting Topics, Special Tools and Appendices. 2*(March 2016), 365. https://ntrs.nasa.gov/search.jsp?R=20170007238

Šajn, N. (2019). Consumers and repair of products. In *European Parliamentary Research Service* (Issue September). http://www.europarl.europa.eu/RegData/etudes/BRIE/2019/640158/EPRS_BRI(2019)640158_EN.pdf

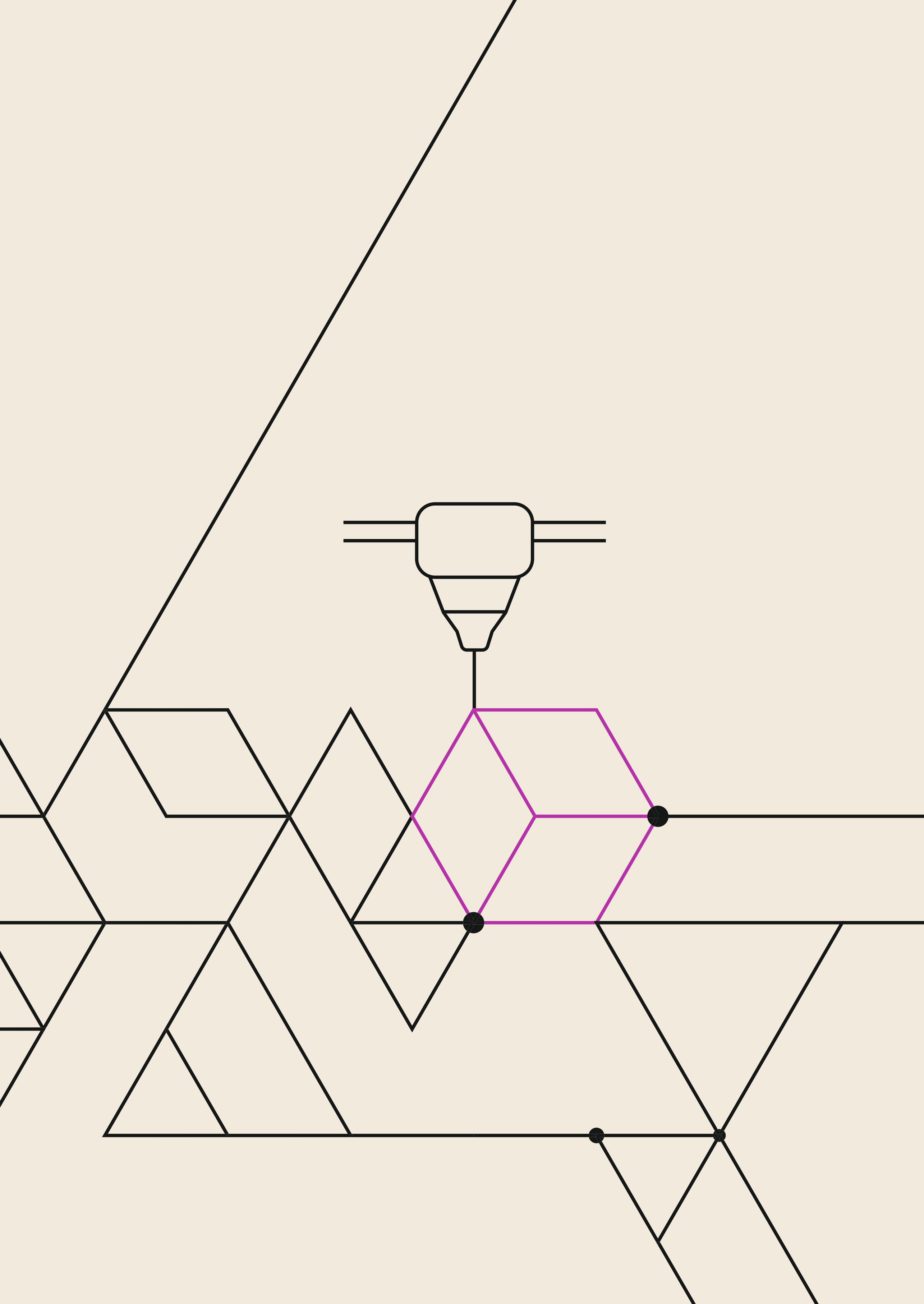
Šajn, N. (2022). Right to Repair. In *European Parliamentary Research Service*. https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/698869/EPRS_BRI(2022)698869_EN.pdf

Svensson-Hoglund, S., Richter, J. L., Maitre-Ekern, E., Russell, J. D., Pihlajarinne, T., & Dalhammar, C. (2021). Barriers, enablers and market governance: A review of the policy landscape for repair of consumer electronics in the EU and the U.S. *Journal of Cleaner Production, 288*. https://doi.org/10.1016/j.jclepro.2020.125488

Van Der Heijden, M., & Iskandar, B. P. (2013). Last time buy decisions for products sold under warranty. *European Journal of Operational Research, 224*(2), 302–312. https://doi.org/10.1016/j.ejor.2012.07.041

van Oudheusden, A., Arriola, J. B., Faludi, J., Flipsen, B., & Balkenende, R. (2023). 3D Printing for Repair : An Approach for Enhancing Repair. *Sustainability, 15*(6), 51–68. https://doi.org/https://doi.org/10.3390/su15065168

Zhang, S., Huang, K., & Yuan, Y. (2021). Spare parts inventory management: A literature review. *Sustainability (Switzerland), 13*(5), 1–23. https://doi.org/10.3390/su13052460



## CHAPTER 5

# Facilitating the production of 3D-printed spare parts in the design of plastic parts: a design requirement review

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The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16219203/s1, Supplementary File S1: Manufacturing capabilities of additive manufacturing compared to injection moulding, Supplementary File S2: Illustrative case.

## ABSTRACT

Using additive manufacturing for spare part production can ensure that spare parts are available for a long time. However, spare parts are currently not designed for additive manufacturing. This study aimed to find how the production of 3D-printed spare parts can be facilitated in the design of plastic parts. We used a literature review and illustrative case to find how the design requirements for standard injection moulded plastic parts relate to the manufacturing capabilities of additive manufacturing for spare parts. The design requirements were defined by assigning corresponding structural and material properties. These requirements were then used to construct and evaluate the capabilities of additive manufacturing compared to injection moulding. It was found that additive manufacturing is especially suitable for requirements like Accuracy, Heat resistance, and Chemical resistance. However, to fully enable 3D-printed spare parts, certain design challenges still need to be tackled. Designers should pay careful attention to the synergies and trade-offs between design requirements and the challenges that might arise from the combination of certain requirements. Also, designers should ensure products are easily reparable before considering 3D-printed spare parts. If we target these challenges in the design phase, we can facilitate 3D-printed spare parts that enable product repairability.

## 5.1 INTRODUCTION

The amount of waste from consumer products is increasing at an alarming rate. There are multiple ways to prevent waste from discarded products, but one key way is to repair them (King et al., 2006; Stahel, 2010). This is mainly because of two reasons: repair slows down resource loops (Bocken et al., 2016), and the required investments are lower than for other recovery options (Scott & Weaver, 2014). However, one of the main problems in repair is that spare parts are not always available (Tecchio et al., 2016; Terzioğlu, 2021). If we want to enable the repair of products, spare parts should be available for most of the product's lifetime.

In Europe, there are regulations to increase the availability of spare parts. These regulations specify that spare parts should be available within 15 working days for 7–10 years after the last market release (European Commission, 2019; Šajn, 2022). However, it is difficult to predict how many spare parts are needed, and storing them in warehouses can be costly (Odedairo, 2021; Yang & Niu, 2009). Some of these parts might not even be used (Behfard et al., 2015), leading to higher costs and more waste (Knofius et al., 2019; Wang et al., 2015). This means that manufacturers need a new way to provide spare parts.



Increasing the availability of spare parts can be achieved with additive manufacturing. This method is increasingly used in the manufacturing industry to produce plastic end-use parts (Salmi & Pei, 2023). Using additive manufacturing means that, instead of keeping a large inventory of physical spare parts, a digital file of each spare part can be stored online and produced on demand (Pérès & Noyes, 2006; Zanoni et al., 2019). This will save costs and waste from unused parts while making them available for a longer period (Holmström & Gutowski, 2017).

While this approach can be used throughout the product, it makes the most sense for product-specific parts. The standardised parts in consumer products, such as nuts, bolts, and springs, are already mass-produced by third parties and are thus always readily available. Additive manufacturing is not a suitable alternative here, as conventional manufacturing of simple parts has lower production costs and lower environmental impact per part at this scale (Faludi et al., 2017; Jung et al., 2023). Conversely, product-specific parts cannot be used outside their target products, which means they are not readily in stock from perpetual mass production. Additionally, these parts are mostly plastic parts made with injection moulding. As injection moulding is unsuitable for on-demand manufacturing (Karania & Kazmer, 2007), these parts would benefit the most from 3D-printed spare parts. Therefore, we chose plastic parts made with injection moulding as the focus of this study.

Using additive manufacturing to produce parts that were initially designed for injection moulding introduces one major challenge: translating the design from one manufacturing method to another. Both the overall product complexity and specific part requirements, such as fine details and flexibility, can make it difficult to reproduce injection moulded parts with additive manufacturing (van Oudheusden, Bolaños Arriola, et al., 2023; van Oudheusden, Buijserd, et al., 2023). Moreover, redesigning spare parts for additive manufacturing after the initial production gives minimal possibilities for design changes and creates an increased workload (Bolaños Arriola et al., 2022; Salmi & Pei, 2023). In the ideal case, printed spare parts would be enabled in the original part design. This means that parts should be designed for both injection moulding and additive manufacturing. However, how can that be achieved easily and effectively?

The main research question is then as follows: how can the production of 3D-printed spare parts be facilitated in the design of plastic parts? This leads to the following research questions for this study:

RQ1. Which design requirements drive the design for both injection moulding and additive manufacturing?

RQ2. How can these design requirements be used to facilitate the design of 3D-printed spare parts?

To answer these research questions, the relationship between design requirements and manufacturing capabilities was studied. We used a literature review to identify which design requirements are relevant and to assess the capabilities of injection moulding and additive manufacturing for these requirements. Then, we performed an illustrative case to show how the results can indicate the suitability of a part for additive manufacturing. By understanding how the design requirements affect the application of additive manufacturing, designers can facilitate the use of additive manufacturing to produce spare parts.

## 5.2 METHOD

Our study was set up in three parts: we created and defined a list of design requirements, assessed the manufacturing capabilities of injection moulding and additive manufacturing for these requirements, and constructed an illustrative case for an exemplary consumer product. As this was an iterative process, the methodology is not presented chronologically.

### 5.2.1 Selecting and Defining Requirements

To find which design requirements drive the design for both injection moulding and additive manufacturing (RQ1), we identified which general design requirements are needed to describe the general functioning of a product part. To do this, the design requirements from previous studies on 3D printing for repair (van Oudheusden, Bolaños Arriola, et al., 2023; van Oudheusden, Buijserd, et al., 2023) were merged and supplemented with an additional literature review. These design requirements were defined further by matching them to relevant structural and material properties.

The cited studies were merged by sorting the requirements into groups and rephrasing them where needed, so they all represented a neutral state. For example, the requirement of Large forces was changed to Strength. The list of requirements was then revised and updated using insights from the literature review and case. This was an iterative process in which requirements were added, removed, and rephrased. The same approach was used to match the design requirements to relevant structural and material properties.

For the supplemental literature review, literature and books on mechanical and material engineering were used. We started with the book Materials: Engineering, Science, Processing and Design (M. Ashby et al., 2014) as this is an essential work on material engineering. Literature was added to this using requirement-specific search terms and further snowballing. For example, queries were along the lines of "Additive Manufacturing OR 3D-printing AND Strength". Literature was accepted or rejected based on whether it provided fundamental insights into the described requirements and manufacturing processes on a commercial application level. During the literature review, it was found that this field is strongly industry-driven and that companies do not often publish their findings in scientific sources. Therefore, to supplement the literature review, we used grey literature such as design rule overviews and technical datasheets (TDSs) of printing materials. These were retrieved from prominent sources: industry leaders like Hubs and Xometry, material manufacturers like Formlabs and 3DSystems, and material databases like Granta Selector.



The resulting design requirements and properties were checked, and any redundancy was removed. Finally, the design requirements and properties were presented in a table. This table was used to define which data needed to be gathered to specify the manufacturing capabilities in the next step.

### 5.2.2 Defining Manufacturing Capabilities

To find out how these requirements can be used to facilitate the design of 3D-printed spare parts (RQ2), we compared the manufacturing capabilities of injection moulding and additive manufacturing. By understanding the gap between the two manufacturing methods and adjusting the design accordingly, it becomes easier to produce 3D-printed spare parts.

We selected three additive manufacturing methods for this study: selective laser sintering (SLS), stereolithography (SLA), and fused deposition modelling (FDM). These methods were chosen as they are commonly available and generally provide good-quality parts (Salmi

& Pei, 2023). This also means that there will be enough information available to judge the capabilities of these methods.

The manufacturing capabilities of these methods were then quantified so they could be compared. This quantification was performed by collecting data on the structural and material properties of each requirement. For the structural properties, data were gathered from manufacturing documentation, such as design guidelines and machine specifications. For the material properties, data were gathered from material databases and technical datasheets. Here, a maximum of four materials were chosen that represented the outer ends of a wider range of suitable materials. The material selection was based on the applicable material properties that were defined for that specific requirement. In this way, we could limit the amount of data while still providing a fair representation of the whole range of possibilities for each requirement.

As there were variations in data quality, each data entry in the table was marked with a data quality score. This score was determined by assessing the data quality and availability, as described in Table 5.1. The assessments of manufacturing capabilities based on lower data quality will be less reliable than those based on high-quality data.

**Table 5.1.** The data quality assessment.

| | | Data Quality Assessment | Example |
|---|---|---|---|
| **1** | High-quality | There are sufficient data on structural and material properties to define the manufacturing capabilities for this design requirement. The material data are retrieved from standardised testing procedures (ASTM/ISO). | SLS has an accuracy of $\pm$0.3% |
| **2** | Medium-quality | There are insufficient data on structural properties to fully define the manufacturing capabilities for this requirement. However, a general assessment can be made using the limited material data from standardised testing methods (ASTM/ISO). | Elastic resins make parts with stretchable and rubber-like properties (50D Shore hardness). |
| **3** | Low-quality | There are insufficient data on structural and material properties to define the manufacturing capabilities for this requirement. Claims are made on material capabilities, but the available data are qualitative and unofficial. | This resilient grade of FDM nylon is highly resistant to shocks and fatigue. |
| **4** | No data | There are no data available, the requirement is rarely mentioned. | Insufficient data. |

Next, we rated all the additive manufacturing methods on each design requirement to find to which degree the requirements affect the application of additive manufacturing. This was performed using the colour-coding system in Table 5.2. The gathered data were presented in a table where each cell was marked with the corresponding colour code. This gives a visual presentation of which requirements limit the application of additive manufacturing the most for a given part versus which requirements are easily managed. In the next step, the illustrative case shows how a designer could use this assessment process to estimate the printability of product parts.

**Table 5.2.** The colour-coding system for the assessment of additive manufacturing (AM) capabilities compared to injection moulding (IM) and the assessment of part printability.

| | Capabilities of Each AM Method Compared to IM (See Section 5.3.2) | Printability Score for Each Part Requirement (See Section 5.3.3) |
|---|---|---|
| **Green** | The capabilities of the AM method are similar to or better than IM. | The part requirement can likely be met with standard materials and post-processing. Likely no design adjustments or verification steps are needed. |
| **Yellow** | The capabilities of the AM method are somewhat inferior to IM (limitations to functionality or performance, especially in the high-end range). | Meeting the part requirement requires more specialised materials and/or extensive processing. Minor design adjustments or verification steps would be needed. |
| **Red** | The capabilities of the AM method are considerably inferior compared to IM, or the requirement is impossible to achieve with this AM method. | The part requirement is (almost) impossible to achieve. Major design changes or verification steps are needed. |
| **Grey** | The manufacturing capabilities cannot be assessed as data quality or availability is too low. | The manufacturing capabilities cannot be assessed as data quality or availability is too low. |

### 5.2.3 Setting Up an Illustrative Case

To illustrate how the results can be applied in the design of consumer products, we performed an illustrative case. The printability of ten exemplary parts from a consumer product was assessed using the insights from the literature review. The consumer product and its parts were selected based on their illustrative properties for the analysis process and their expected printability. The printability of these parts was then assessed by comparing their part requirements against the manufacturing capabilities from the literature review. Finally, we concluded what the main points of attention would be when this part would be designed for both injection moulding and additive manufacturing.

We chose to study a high-end vacuum cleaner as the European Commission is developing new eco-design regulations for this product category (Cordella et al., 2019; European Parliament, 2024). Also, the complexity of this product will give valuable insights into the printability of consumer products and the issues that might be encountered. From this vacuum cleaner, we chose the following ten parts: the bumper, LED cover, wheel suspension frame, brush locking cap, back cable cover, hinge, wheel and brush of the floor nozzle, and the container and inlet seal of the dustbin. These parts were selected to present a variety of design requirements and part complexity. Generally, all parts could be fully disassembled to give a fair overview of the capabilities and limitations of additive manufacturing rather than of reparability. However, one submodule was selected to explore the challenges that these submodules might pose for the application of additive manufacturing.

The selected parts were analysed in more detail. First, each part was analysed on the list of design requirements using visual inspection and a calliper. The observed requirements and properties were all marked in an annotated photo of the part. This was performed to see whether all part features were covered by the design requirements table and to obtain more insight into the interaction between requirements. Then, the part material was identified through material code observation or Fourier-transform spectroscopy (FTIR) to give a representable material selection. A representative printing material was selected for each part based on the applicable requirements and the original material. For this, we used Supplementary File S1 and additional insights from the material data collection in the literature review.

We collected and structured the assessment findings in a data table for each part. The first column listed the design requirements of this study, and the three consecutive columns noted the part requirements and how likely SLA, SLS, and FDM were to meet these requirements. This was performed by comparing the requirements for each design requirement against the capabilities of the manufacturing methods from the previous step. We then visualised this assessment by applying the corresponding colour code from Table 5.2. Finally, the bottom two rows of the table listed the major part requirements and concluding remarks on the estimated printability of each part.

The next section will present the results of these steps. Using these results, we can define how 3D-printed spare parts can be facilitated in the design phase of the product.

## 5.3 RESULTS

The relationship between design requirements and manufacturing capabilities was investigated through two tables. Table 5.3 creates an overview of the design requirements, and Table 5.4 defines the manufacturing capabilities for these requirements. The insights from Table 5.4 were then applied in a case to illustrate how designers can use the findings to facilitate 3D-printed spare parts in the original design.

**Table 5.3.** Summary of design requirements, with examples of structural and material properties, for plastic injection-moulded spare parts. "..." indicates more properties are listed for that requirement in the full version; see Appendix A for the full version of this table.

| Design Requirement | Structural Properties Example | Material Properties Example |
|---|---|---|
| *Geometry* | | |
| Shape | Overhang<br>Cavities<br>... | Thermal expansion rate<br>Linear mould shrinkage |
| Detail | Minimum wall thickness<br>Minimum feature size<br>... | Thermal expansion rate<br>Linear mould shrinkage |
| | See also: Accuracy and Tolerances | |
| Accuracy and tolerances | Part tolerance<br>Part clearance<br>... | Thermal expansion rate<br>Material shrinkage<br>Linear mould shrinkage |
| *Configuration* | | |
| Water-/airtightness | Wall thickness<br>Porosity/gaps<br>... | Permeability ($O_2$/$CO_2$/$N_2$) |
| | See also: Accuracy and Tolerances, Surface finish | |
| Multi-material | Inserts<br>Fastening feature/mechanical bond<br>Surface smoothness | Material compatibility<br>Material shrinkage<br>... |
| Surface finish | Surface finish<br>Surface texture | Friction coefficient<br>Self-lubrication |
| Transparency | Microstructure<br>Wall thickness<br>... | Transparency<br>Haze<br>... |
| | See also: Surface finish | |
| *Mechanical requirements* | | |
| Strength | Part/feature size<br>Wall thickness<br>... | Tensile strength<br>Young's modulus<br>... |
| Flexibility (bend) | Length<br>Cross-sectional area<br>... | Young's modulus<br>Flexural strength<br>... |
| Elasticity (stretch/ compress) | Length<br>Cross-sectional area<br>Microstructure | Young's modulus<br>Elongation at break<br>... |
| Impact resistance | Stress concentrators<br>Wall thickness (optimization)<br>... | Fracture toughness<br>Impact strength (Izod, Charpy)<br>... |

**Table 5.3.** Summary of design requirements, with examples of structural and material properties, for plastic injection-moulded spare parts. "…" indicates more properties are listed for that requirement in the full version; see Appendix A for the full version of this table. (continued)

| **Design Requirement** | **Structural Properties Example** | **Material Properties Example** |
|---|---|---|
| Abrasion resistance | Microstructure<br>Surface roughness<br>… | Hardness<br>Abrasion resistance (Tabor)<br>… |
| | See also: Surface finish | |
| Fatigue resistance | Stress concentrators<br>Compressive surface stress<br>… | Fracture toughness<br>Fatigue limit at $10^7$ cycles<br>… |
| Creep resistance | Part geometry<br>Stress concentrators<br>Fillet/chamfer radius | Creep resistance<br>Glass temperature<br>… |
| *Thermal requirements* | | |
| Heat resistance | Part/feature thickness<br>Part volume | Glass temperature<br>Heat deflection temperature<br>… |
| Cold resistance | Part/feature thickness<br>Part volume | Ductile/brittle transition temperature<br>Minimum service temperature<br>… |
| *Chemical requirements* | | |
| Water resistance | Crevices<br>Porosity/gaps<br>… | Water absorption<br>Permeability ($O_2$/$CO_2$/$N_2$)<br>… |
| | See also: Detail, Surface finish | |
| UV resistance | — | UV resistance<br>Indoor stability<br>… |
| Chemical resistance | Crevices<br>NEMA-rating | Chemical resistance index<br>Environmental stress crack index<br>… |
| | See also: Detail, Surface finish | |
| Food safety | Crevices<br>Corner radii<br>… | Food contact grade<br>Sterilizability |
| | See also: Detail, Surface finish, Chemical resistance | |

**Table 5.4.** Summary of manufacturing capabilities for meeting the design requirements from Table 5.3. See Supplementary File S1 for the full version of this table. The footnotes indicate the following data quality for that requirement: 1 = High-quality data, 2 = Medium-quality data, 3 = Low-quality data, 4 = No data available.

| Design Requirement | Injection Moulding (IM) | Stereo-Lithography (SLA) | Selective Laser Sintering (SLS) | Fused Deposition Modeling (FDM) |
|---|---|---|---|---|
| *Geometry* | | | | |
| Shape [1] | High form freedom, draft needed. | High form freedom, but support needed. [1] | High form freedom, no support needed. [1] | Good form freedom, but support is needed. [1] |
| Detail [1] | Min. wall size: 0.8–1.2 mm, min. feature size: 0.4–0.6 mm. | Min. wall/ feature size: 0.1–0.4 mm. [1] | Min. wall/ feature size: 0.8 mm. [1] | Min. wall/ feature size: 1.1–1.5 mm. [1] |
| Accuracy and tolerances [1] | Typically ±0.25 mm, can go as low as ±0.025–0.125 mm. | Accuracy of ±0.15% (min. 0.01–0.03 mm) for industrial machines. [1] | Accuracy of ±0.3% (min. 0.3 mm) for industrial machines. [1] | Accuracy of ±0.15% (min. 0.2 mm) for industrial machines. [1] |
| *Configuration* | | | | |
| Water/air tightness [1] | Water- and airtight when using the recommended wall thicknesses. | Properly printed parts are waterproof and airtight. [1] | Parts have a porous surface and need additional post-processing. [1] | Parts have a porous microstructure and need additional post-processing. [1] |
| Multi-material [1] | Multiple options (e.g., insert-, 2K-, and overmoulding). | Only on lab-scale. [1] | Only on lab-scale. [1] | Multiple-material extrusion is possible. [1] |
| Surface finish [1] | Smooth finish possible (Ra = 0.012–0.7 μm for parts with a polished finish). | Smooth finish possible (Ra ≈ 0.4–2.3 μm). [1] | Rougher finish, even after post-processing (Generally around Ra ≈ 2.3–5.7 μm). [1] | Rougher finish, even after post-processing. Large variations (Ra = 0.9–22.5 μm, side planes are roughest). [1] |
| Transparency [1–2] | Wide range from opaque to fully transparent | Wide range from opaque to fully transparent. [2] | All parts are opaque. [1] | Ranges from opaque to translucent. Visible layer lines, part needs post-processing. [2] |

**Table 5.4.** Summary of manufacturing capabilities for meeting the design requirements from Table 5.3. See Supplementary File S1 for the full version of this table. The footnotes indicate the following data quality for that requirement: 1 = High-quality data, 2 = Medium-quality data, 3 = Low-quality data, 4 = No data available. (continued)

| Design Requirement | Injection Moulding (IM) | Stereo-Lithography (SLA) | Selective Laser Sintering (SLS) | Fused Deposition Modeling (FDM) |
|---|---|---|---|---|
| *Mechanical requirements* | | | | |
| Strength [1] | Various high-strength polymers are available (e.g., PEI, PEK); tensile strength around 92–120 MPa. Strength is isotropic. | Generally brittle materials, but stronger resins exist (e.g., tough and durable resins), tensile strength around 61–65 MPa. Strength is near-isotropic. [1] | Generally strong materials, tensile strength around 29–69 MPa. Printed parts are not as strong as IM. Strength is slightly anisotropic. [1] | Strong materials (e.g., PEI, PC), tensile strength around 48–81 MPa. Strength is highly anisotropic due to limited layer adhesion. [1] |
| Flexibility [2] | Ranging from stiff plastic to hard rubber to very soft elastomer polymers; Young's modulus between 0.2–50 MPa. | Ranging from stiff polymeric to hard rubber-like to softer silicone-like materials, Young's modulus between <1–10 MPa. [2] | Stiff polymeric to hard rubber-like materials available, Young's modulus between 5.3–131 MPa. [2] | Ranging from stiff plastic to hard rubber-like to softer silicone-like materials, Young's modulus between 15.3–205 MPa. [2] |
| Elasticity [2] | There are various polymers with very high elongation at break (80–1780%). Stretch is isotropic. | There are resins with relatively high elongation at break (160–300%). Stretch is near-isotropic. [2] | There are powders with high elongation at break (60–500%). Stretch is anisotropic. [2] | There are filaments with very high elongation at break (150–950%). Stretch is anisotropic (risk of layer delamination). [2] |
| Impact resistance [2] | There are various impact-resistant polymers (e.g., PAI, HIPS); notched impact strength >500 J/m. | Engineering resins (e.g., tough, durable, rigid PU) have good impact resistance; notched impact strength between 17–375 J/m. [2] | Lower impact strength due to porous surface (needs post-processing). There are various impact-resistant powders (e.g., PA11, PAx); notched impact strength between 32–71 J/m. | Lower impact strength due to bad layer adhesion. There are various impact-resistant filaments (e.g., ABS, PC-ABS); notched impact strength ranging between 32.2–241 J/m. |
| Abrasion resistance [3] | There are various wear-resistant (e.g., PA) and self-lubricating (e.g., UHMW-PE) polymers available. | Insufficient data. Claims of high wear resistance for durable resins. [3] | Insufficient data. Claims of good wear resistance for some materials (e.g., PA, PEEK). [3] | Insufficient data. Claims of high wear resistance for some materials (nylon, PEKK). [3] |

**Table 5.4.** Summary of manufacturing capabilities for meeting the design requirements from Table 5.3. See Supplementary File S1 for the full version of this table. The footnotes indicate the following data quality for that requirement: 1 = High-quality data, 2 = Medium-quality data, 3 = Low-quality data, 4 = No data available. (continued)

| Design Requirement | Injection Moulding (IM) | Stereo-Lithography (SLA) | Selective Laser Sintering (SLS) | Fused Deposition Modeling (FDM) |
|---|---|---|---|---|
| Fatigue resistance [3] | There are various fatigue-resistant polymers (e.g., POM, PEEK). Defects (e.g., knit lines) can affect fatigue strength | Insufficient data. Claims of good fatigue properties for some materials (e.g., Accura resins). [3] | Insufficient data. Claims of good fatigue properties for some materials (e.g., PP). [3] | Insufficient data. Claims of good fatigue properties for some materials (e.g., PA, PEEK). Needs post-processing to offset layer adhesion /surface defects. [3] |
| Creep resistance [3–4] | There are various creep-resistant polymers (e.g., PC) | Insufficient data. Common resins may creep, but some resins (e.g., rigid ceramic resins) claim to be more creep-resistant. [3] | Insufficient data. Additives are said to give a material a higher creep resistance. [4] | Insufficient data. Claims of filaments being more susceptible to creep due to their low melting point. [3] |
| *Thermal requirements* | | | | |
| Heat resistance [1] | There are multiple heat-resistant polymers available (e.g., PAI, PEEK), service temperature between 161–260 °C. | Generally low heat resistance, but there are heat-resistant resins with heat deflection temperature between 200–300 °C (might require thermal curing). [1] | All materials are heat-resistant, service temperature typically between 150–185 °C, but can go up to over 300 °C. [1] | General service temperature between 50–120 °C. More heat-resistant filaments (e.g., PC, PEI) have an HDT between 133–214 °C. [1] |
| Cold resistance [4] | Difficult to determine, but most engineering plastics besides PP and PET are well suited to temperatures below zero. | Insufficient data. In experimental testing, strong resin was unaffected by prolonged exposure below zero. | Insufficient data. | Insufficient data. Essentium claims their Altitude filament can withstand −60 °C. |

**Table 5.4.** Summary of manufacturing capabilities for meeting the design requirements from Table 5.3. See Supplementary File S1 for the full version of this table. The footnotes indicate the following data quality for that requirement: 1 = High-quality data, 2 = Medium-quality data, 3 = Low-quality data, 4 = No data available. (continued)

| Design Requirement | Injection Moulding (IM) | Stereo-Lithography (SLA) | Selective Laser Sintering (SLS) | Fused Deposition Modeling (FDM) |
|---|---|---|---|---|
| *Chemical requirements* | | | | |
| Water resistance [1] | There are various polymers (e.g., HDPE, PP) with little to no water absorption (<0.1%). | Virtually no porosity. There are various materials with low water absorption (<0.1–0.35%). [1] | Additional finishing is required to offset surface porosity. Most powders have low water absorption (around/below 0.1%). [1] | Additional finishing is required to offset layer gaps. Various filaments (e.g., PETG, PP) have low water absorption (between 0.23–1%). [1] |
| UV resistance [3] | A few polymers have UV resistance of tens of years (e.g., PEI, PAI). | Insufficient data. Resins are sensitive to UV degradation (embrittlement and yellowing). [3] | Insufficient data. Claims of UV resistance for some powders (e.g., nylon, TPU). [3] | Insufficient data. Claims of UV resistance for some filaments (e.g., ASA, PVDF). [3] |
| Chemical resistance (household) [2] | There are various polymers with excellent chemical resistance (e.g., PEEK, PP). | Most resins have good chemical resistance for most household chemicals. [2] | Most materials (e.g., PA, PP) have good chemical resistance for most household chemicals. [2] | Most engineering filaments (e.g., PP) have good chemical resistance for most household chemicals. [2] |
| Food safety [1] | There are various food-grade polymers (e.g., PC, PP), parts need to adhere to strict production regulations. | Resins are not food-safe due to their toxicity. Coating is insufficient to guarantee food safety. [1] | Certified food-grade printing of PA11/12 is possible, but options are limited. [1] | Food-safe filaments are available, but there is no certified production process. Layer lines pose a risk for bacteria buildup. [1] |

*[1] = High-quality data, [2] = Medium-quality data, [3] = Low-quality data, [4] = No data available. The colour-coding in the cell indicates the following regarding the capabilities for each additive manufacturing method compared to injection-moulding: green = similar or better, yellow = slightly inferior, red = considerably inferior or impossible, and grey = insufficient data (quality) for assessment.*

### 5.3.1 Design Requirements

The full table of design requirements that designers would use is too long to display here; it is shown in Appendix A and summarised in Table 5.3. Table 5.3 gives an overview of the selected design requirements, each with an example of relevant structural and material properties. This summary table should be sufficient to construct a general definition of the design requirements.

Appendix A, summarised in Table 5.3, lists a total of 20 requirements that are divided into five groups. The appendix presents a more complete overview of structural and material properties for each design requirement, including citations. To give an example, for the requirement Shape, Appendix A lists nine structural properties (Size, Wall thickness uniformity, Undercuts/overhang, Horizontal bridges, Internal channels, Part thickness/shell, Feature spacing, Pockets and cavities, and Draft angles (IM only)) and two material properties (Thermal expansion coefficient and Linear mould shrinkage). Additionally, the cross-references in Table 5.3 and Appendix A indicate a larger overlap between design requirements, such as for Detail and Food safety. Using these requirements, we can define the capabilities of additive manufacturing in the next section.



### 5.3.2 Manufacturing Capabilities

The full table of manufacturing capabilities that designers would use is too long to display here; it is shown in Supplementary File S1 and summarised in Table 5.4. Table 5.4 assesses the manufacturing capabilities of injection moulding and additive manufacturing for the design requirements in Table 5.3. Though only a summary, Table 5.4 should be sufficient to compare the manufacturing capabilities of injection moulding and additive manufacturing.

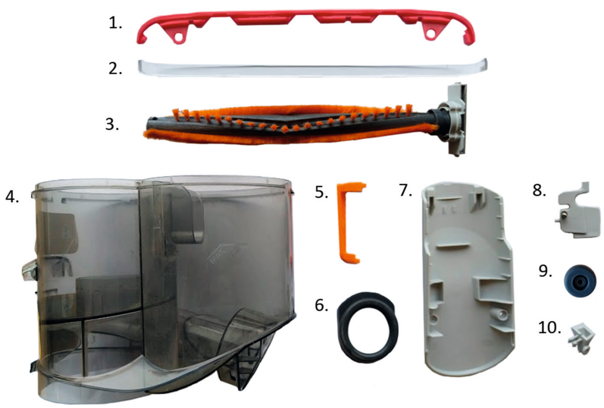
Supplementary File S1, summarised in Table 5.4, gives a high-level overview of which design requirements are generally achievable and which ones are more challenging for additive manufacturing. The supplementary file presents a more detailed overview of the manufacturing capabilities for each design requirement, including citations. To give an example, for the design requirement Shape, Supplementary File S1 lists what each manufacturing method is capable of in terms of form freedom, use of support structures, corners, overhang and bridging, drainage holes, and common printing defects that affect the shape. From this analysis, we concluded that FDM printing is less capable of replicating complex geometries than injection moulding, as FDM printing is more prone to printing defects (Protolabs Network, 2024b). This meant that FDM printing was marked yellow for this requirement. The capabilities of SLA and SLS printing were more comparable to those of injection moulding and were, therefore, both marked green. The design requirements that were marked green for most printing methods were Accuracy, Heat resistance, and Chemical resistance. Conversely, requirements that were mostly marked red were Multi-material and Food safety.

There were variations in the data quality for the various requirements, as indicated by the footnotes in Table 5.4. For 16 out of 20 requirements, sufficient information was available to estimate the capabilities of additive manufacturing. This made it easy to determine the relative capabilities of additive manufacturing compared to injection moulding. Some of these requirements could be better defined with extended material data. For instance, for Flexibility, the data sheets report obscure material properties, such as Shore hardness, rather than more representative properties like Young's modulus or flexural strength. Still, the relative manufacturing capabilities for these requirements could be estimated through the available data and observation of the demonstrated material behaviour. For the remaining four requirements, the data were low-quality or not available. This was mostly the case for mechanical requirements, such as Abrasion resistance and Creep resistance. For example, Supplementary File S1 lacks citations for requirement-specific properties for Abrasion resistance, such as the wear constant or wear rate. As a result, the capabilities of additive manufacturing for these requirements could not be estimated.

The manufacturing capabilities described in Supplementary File S1 (summarised in Table 5.4) represent the general performance of each manufacturing method using standard operating parameters. The table should not be seen as a look-up table, nor is it depicting the ultimate performance of additive manufacturing. Instead, it helps designers to evaluate which areas require more attention during the (re)design phase. For example, while injection moulding can achieve very high accuracy, in most cases, its accuracy is comparable to that of industrial-level additive manufacturing. This means that accuracy will only be a point of attention for specific features that require high accuracy, such as press fits and snap fits. These part features can likely still be achieved with additive manufacturing, but they will need more careful design optimisation. These assumptions were verified in the illustrative case.

### 5.3.3 Illustrative Case

Figure 5.1 shows the ten exemplary parts of the vacuum cleaner that were selected to illustrate the use of the table. The manufacturability of these parts as 3D-printed spare parts was assessed by comparing their part requirements against the manufacturing capabilities in Table 5.4. The results are presented below in Tables 5 and 6. The full study on the printability for each part, which discusses the applicable requirements and printability scores in more detail, can be found in Supplementary File S2. The assessment presented below is intended to provide an overview of part printability.




1. Floor nozzle bumper
2. Floor nozzle LED cover
3. Floor nozzle brush
4. Dustbin container
5. Floor nozzle locking cap
6. Dustbin inlet seal
7. Floor nozzle cable cover
8. Floor nozzle hinge
9. Floor nozzle wheel
10. Wheel suspension

**Figure 5.1.** Parts selected for the illustrative case.

**Table 5.5.** Summary of assessments of part printability for parts 1-5. For full assessments, see Supplementary File S2.

| | 1. Floor Nozzle Bumper | | | 2. Floor Nozzle LED Cover | | | 3. Floor Nozzle Rotating Brush | | | 4. Dustbin Container | | | 5. Floor Nozzle Brush Locking Cap | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| |  | | |  | | |  | | |  | | |  | | |
| Original Material | PP | | | PC | | | Nylon + PP + POM | | | Glass-Filled ABS | | | ABS | | |
| SLA Material * | Durable (PP-Like) resin | | | Clear resin | | | Durable (PP-Like) resin | | | Clear resin | | | Durable (PP-Like) resin | | |
| SLS Material | PA11 | | | PA11 | | | PA12 | | | PA11 | | | PA11 | | |
| FDM Material | ABS | | | Clear PETG | | | Nylon | | | Clear PC | | | Nylon | | |
| AM Method | SLA | SLS | FDM | SLA | SLS | FDM | SLA | SLS | FDM | SLA | SLS | FDM | SLA | SLS | FDM |
| Shape | | | | | | | | | | | | | | | |
| Detail | | | | | | | | | | | | | | | |
| Accuracy and tolerances | | | | | | | | | | | | | | | |
| Water/air-tightness | | | | | | | | | | | | | | | |
| Multi-material | | | | | | | | | | | | | | | |
| Surface finish | | | | | | | | | | | | | | | |
| Transparency | | | | | | | | | | | | | | | |
| Strength | | | | | | | | | | | | | | | |
| Flexibility | | | | | | | | | | | | | | | |
| Elasticity | | | | | | | | | | | | | | | |
| Impact resistance | | | | | | | | | | | | | | | |

**Table 5.5.** Summary of assessments of part printability for parts 1-5. For full assessments, see Supplementary File S2. (continued)

| | 1. Floor Nozzle Bumper | 2. Floor Nozzle LED Cover | 3. Floor Nozzle Rotating Brush | 4. Dustbin Container | 5. Floor Nozzle Brush Locking Cap |
|---|---|---|---|---|---|
| Abrasion resistance† | | | | | |
| Fatigue resistance † | | | | | |
| Creep resistance † | | | | | |
| Heat resistance | | | | | |
| Cold resistance | | | | | |
| Water resistance | | | | | |
| UV resistance † | | | | | |
| Chemical resistance | | | | | |
| Food safety | | | | | |
| Major part requirement(s) | – | Transparency<br>Surface finish | Multi-material<br>Abrasion resistance | Impact resistance<br>Shape | Strength<br>Flexibility<br>Accuracy |
| Concluding remarks | The shape, detail, and semi-rigid flexibility/flexural strength should be achievable with all printing methods. | Limited printing options as full transparency is required for technical functioning. | Part complexity is too high. The bristles are not replicable with any printing method. | The inlet cavity's complex shape combined with the transparency makes the part difficult to replicate with any printing method. | Printable, but the high flexural strength and accurate details will be difficult to achieve. |

** SLA resins are thermosets but often characterised as "thermoplastic-like", e.g., durable resins are "PP-like". † Insufficient data in Table 5.4 to conclude. The colour-coding in the cell indicates the following regarding part manufacturability: green = likely possible with standard manufacturing and little design adjustments, yellow = could be possible with careful consideration of manufacturing and design, red = almost impossible without major design changes, grey = insufficient data (quality) for assessment.*

**Table 5.6.** Summary of assessments of part printability for parts 6-10. For full assessments, see Supplementary File S2.

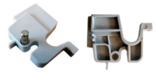
| | 6. Dustbin Inlet Seal | | | 7. Floor Nozzle Back Cable Cover | | | 8. Floor Nozzle Hinge | | | 9. Floor Nozzle Wheel | | | 10. Floor Nozzle Wheel Suspension | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| |  | | |  | | |  | | |  | | |  | | |
| Original material | PDMS (Silicone) | | | ABS | | | POM + Metal Pin | | | PP + LDPE | | | PTFE (Teflon) | | |
| SLA material * | Rebound resin | | | Tough (ABS-Like) resin | | | Durable (PP-Like) resin | | | Tough resin + Flexible resin | | | Durable (PP-Like) resin | | |
| SLS material | TPU | | | PA12 | | | PA12 | | | PA12 + TPU | | | PA11 | | |
| FDM material | TPE | | | Nylon | | | Nylon 66 | | | ABS + TPU | | | Nylon | | |
| AM Method | SLA | SLS | FDM | SLA | SLS | FDM | SLA | SLS | FDM | SLA | SLS | FDM | SLA | SLS | FDM |
| *Shape* | | | | | | | | | | | | | | | |
| *Detail* | | | | | | | | | | | | | | | |
| *Accuracy and tolerances* | | | | | | | | | | | | | | | |
| *Water/air-tightness* | | | | | | | | | | | | | | | |
| *Multi-material* | | | | | | | | | | | | | | | |
| *Surface finish* | | | | | | | | | | | | | | | |
| *Transparency* | | | | | | | | | | | | | | | |
| *Strength* | | | | | | | | | | | | | | | |
| *Flexibility* | | | | | | | | | | | | | | | |
| *Elasticity* | | | | | | | | | | | | | | | |

**Table 5.6.** Summary of assessments of part printability for parts 6-10. For full assessments, see Supplementary File S2. (continued)

| | 6. Dustbin Inlet Seal | 7. Floor Nozzle Back Cable Cover | 8. Floor Nozzle Hinge | 9. Floor Nozzle Wheel | 10. Floor Nozzle Wheel Suspension |
|---|---|---|---|---|---|
| *Impact resistance* | | | | | |
| *Abrasion resistance†* | | | | | |
| *Fatigue resistance †* | | | | | |
| *Creep resistance †* | | | | | |
| *Heat resistance* | | | | | |
| *Cold resistance* | | | | | |
| *Water resistance* | | | | | |
| *UV resistance†* | | | | | |
| *Chemical resistance* | | | | | |
| *Food safety* | | | | | |
| Major part requirement(s) | Flexibility<br>Elasticity<br>Strength | Accuracy<br>Impact resistance<br>Strength | Surface finish<br>Abrasion resistance<br>Multi-material | Abrasion resistance<br>Surface finish | Strength<br>Flexibility |
| Concluding remarks | The combination of part requirements for the (dis)- assembly process will be challenging to achieve, especially for SLS. | The part is printable but further testing is needed to see if the snap-fit strength and general impact strength are sufficient. | The metal pin makes the part more complex to print. For higher abrasion resistance, a different material or external lubrication might be needed. | The two different materials make the part more complex to print. Either a multi-material or multi-component part is needed. | The required flexural force and fatigue resistance for the snap-fits will be challenging to replicate for most printing methods. |

** SLA resins are thermosets but are often characterised as "thermoplastic-like", e.g., durable resins are "PP-like". † Insufficient data in Table 5.4 to conclude. The colour-coding in the cell indicates the following regarding part manufacturability: green = likely possible with standard manufacturing and little design adjustments, yellow = could be possible with careful consideration of manufacturing and design, red = almost impossible without major design changes, grey = insufficient data (quality) for assessment.*

The overview in Table 5.5 and Table 5.6 presents how Table 5.4 has been used to identify potential tensions between the part designed for injection moulded and the 3D printed spare part (without any redesign). If a part is green for all relevant properties, 3D printing is expected to be straightforward. If a few indicators are yellow, a redesign is likely needed. Red indicates that the part cannot be 3D printed without extensive redesign. Below, a few examples of ratings are discussed to illustrate the assessment process. It should be noted that the assessments below are based on assumptions, whereas product designers would be able to make these assessments more accurately.

- For the floor nozzle bumper, the part requirements for Shape and Detail are easy to achieve. There is no overhang or other complex geometry, and the part details range between 1 and 2 mm. This is well within the capabilities of additive manufacturing, as all manufacturing methods can print a detail size of around 1 mm. Therefore, these requirements are rated green.
- For the floor nozzle brush, the part requirements for Multi-material are almost impossible to achieve. The part has numerous subcomponents made from different materials and assembled through moving connections. The brush could be printed as separate components up to a certain point, but the overmoulded bristles will be impossible to replicate with additive manufacturing. Therefore, this requirement is rated red.
- For the dustbin inlet seal, the part requirements for Flexibility and Elasticity will be difficult to achieve. The part requires the properties of a soft and stretchable elastomer, as it needs to stretch and compress during installation and removal. Both SLA and FDM printing offer soft and stretchable elastomers; however, without further testing, it is not possible to verify whether these materials can meet these specific part requirements.
- For the wheel suspension, the specific combination of part requirements will be challenging to achieve. The snap-fits require a tailored combination of strength, flexibility, accuracy, and surface finish in a localised section of the part. Conversely, the section of the part that connects to the rotating wheel axle requires very high abrasion resistance and a smooth surface finish. Even if each requirement is feasible separately, the designer should still be mindful of the trade-offs and synergies between the part requirements, as reflected in the concluding remarks.

## 5.4 DISCUSSION

The results show that additive manufacturing has potential for spare parts production, but specific design considerations are needed for many of the requirements. Additive manufacturing is generally well-suited for requirements like Accuracy, Heat resistance, and Chemical resistance. Only a few of the identified requirements, like Multi-material and Food safety, will always be challenging with additive manufacturing. This can also be seen in the illustrative case. Although only the floor nozzle bumper printed in SLA is completely marked green, there are rarely any squares marked red. Most parts score a mix of green and yellow. This suggests that additive manufacturing is not simply a drop-in replacement for injection moulding, but most of the challenges posed by the design requirements could be overcome through careful design. For legacy parts or redesigns, it is a question of how much design time and effort the part is worth. However, for new product designs with increased design freedom, the tables can guide designers on how to facilitate printed spare parts in the design of the parts.

Table 5.4 highlights where specific design attention may be required. Designers can find which of the requirements for a particular spare part might need more careful design consideration by comparing the part requirements against the manufacturing capabilities in Table 5.4. Designing the part can go in two directions:

- The original part is designed to be suitable for both injection moulding and additive manufacturing;
- Two different yet interchangeable part designs are made, with the original part optimised for injection moulding and the spare part optimised for additive manufacturing.

How challenging the (re-)design process will be depends on the gap between part requirements and manufacturing capabilities, colour-coded green/yellow/red in Table 5.4.

Most of the relevant design requirements that drive the design for both injection moulding and additive manufacturing are listed in Table 5.3. While there are potentially an infinite number of design requirements, the illustrative case demonstrated that most requirements are covered by a limited number of requirements. Indeed, most parts in the illustrative case were driven by a small subset of Table 5.3's properties. This indicates that the design for 3D-printed spare parts could mostly be managed by developing design strategies for the more common design requirements.

Still, designers should consider what other requirements might be relevant to their part. It could be that specific parts have requirements that are not commonly encountered in consumer products, such as electrostatic discharge (ESD) resistivity, vibration dampening, or cleanability for sterilisation. Additionally, part requirements could go beyond the technical functioning: user experience can be equally important, especially for cosmetic parts. For example, the transparency of the dustbin, in this case, is technically not required, as the product would still work without it. However, it might affect the user experience, as users can only check the contents of the dustbin after removing it first. This is different from the transparency required by the LED cover. This cover protects an LED strip at the front of the floor nozzle, whose directional beam of light is used to reveal hidden dust and dirt. Omitting the transparency of the cover would, therefore, affect the product performance. Other experiential requirements could include certain visual or tactile experiences. In most cases, these additional requirements will be related to the properties and requirements already defined in Table 5.3. For example, the gloss of a part is related to the surface finish and corresponding properties such as the refractive index.

While the design requirements are listed separately in these tables, it is important to realise that a part is defined through the combination of requirements. Often, part properties are related to more than one design requirement. For example, the friction coefficient of a material is related to both surface finish and abrasion resistance. This interaction between design requirements can also be seen in the illustrative case. In this case, the snap-fits of the wheel suspension combine flexural strength and semi-rigid flexibility, and the soft-touch finish of the wheel combines surface finish, flexibility, and elasticity. Therefore, it is not sufficient if a manufacturing method has good scores for just a few design requirements. The whole range of applicable design requirements should be considered when enabling 3D-printed spare parts in the part design.

Some design requirements will be more difficult to combine than others. For example, the dustbin, in this case, requires a combination of transparency and impact resistance. Only SLA can manage near-optical transparency, but transparent SLA resins are known to be more brittle than opaque resins. So, while SLA scores relatively well on both transparency and impact resistance in Table 5.4, this part will still be challenging to design due to the combination of requirements. Similarly, combining food safety and fine details will be challenging, as there is no additive manufacturing method in Table 5.4 with high scores for both. As such, the specific combination of design requirements in a part can also influence which additive manufacturing method should be used or whether any are viable.

Future technical developments could shift manufacturing capabilities. Requirements that are difficult or (near)-impossible to achieve, such as transparent SLS printing, could become more accessible. As the capabilities of additive manufacturing expand in the future, it will become easier to facilitate 3D-printed spare parts in the design of injection-moulded parts.

Of course, if products or their major components are not practical to repair even with perfect spare parts, it does not make sense to consider additive manufacturing for the production of spare parts. Design for repair should be prioritised over 3D-printed spare parts for products that are not suitable for repair.

### 5.3.4 Limitations and Recommendations

The varying availability and quality of data on additive manufacturing methods and materials made it difficult to make an accurate comparison between additive manufacturing and injection moulding. The material properties in the technical datasheets used different data units and were not obtained by the same testing methods, testing conditions, and testing standards. Also, the information in the technical datasheets was not always sufficient to assess additive manufacturing capabilities for certain requirements. Moreover, it is not sufficient to rely on material data alone. The manufacturing process and printing settings will also influence most of the design requirements, but these insights were not always available.



More research is needed to obtain data on the capabilities of additive manufacturing for the design requirements that are currently inconclusive or have poor data quality. This will help to better determine to what extent particular design requirements can be met. Achieving this goal requires a collaboration between industry and scientific research and possibly an update of industry standards. Until more data are available, it is recommended that designers do additional testing and collaboration with material developers to overcome the lack of insight or limit themselves to well-understood solutions. Further research could also consider a broader range of materials and processes for the production of spare parts, using the insights from this study. Additionally, to make the information enclosed in this paper more directly applicable to designers, we recommend that further research focuses on creating design guidelines to help designers navigate the design challenges that were identified in this study.

## 5.4 CONCLUSION

The aim of this study was to find how the production of 3D-printed spare parts can be facilitated in the design of plastic parts. This study shows how additive manufacturing has the potential to produce spare parts for the plastic parts in consumer products. However, it is not a simple drop-in replacement, is sometimes impossible, and usually requires some part redesign or careful selection of the additive manufacturing method and material. To support designers, a good understanding of the design requirements and manufacturing capabilities for both methods is needed, as presented in this study. The manufacturing capabilities in Table 5.4 (Supplementary File S1) will help designers estimate how challenging the adaptation will be and, thus, whether it is worth their time and effort. The colour-coding in this table, which represents the differences between injection moulding and manufacturing, can also help designers to optimise their design for 3D-printed spare parts.

When designing printed spare parts, designers should always consider the trade-offs and synergies between design requirements and the challenges that could arise from trying to meet combinations of certain requirements. Rather than a single complex requirement, it will be the complexity of the design that will make it difficult to design a printable spare part. This represents a larger design challenge, where designers need to be fluent in both design for injection moulding and design for additive manufacturing to be able to adapt the design correspondingly. By realising printed spare parts for easier parts first, we can optimise the design process and find ways to make designers more familiar with the process. Moreover, designers should ensure products are easily repairable before considering 3D-printed spare parts. Considering the production of spare parts during the design process is the next step in designing a repairable product and preventing waste.

## 5.5 APPENDIX A

Below, Table A1 gives examples to illustrate the design requirements, as well as structural and material properties, that designers should need to take into account. This table does not pretend to be comprehensive, as there are too many design variables and properties that would need to be discussed. For some properties, the depth of study was limited. Especially for water tightness, it was difficult to find qualitative sources to cite, despite the common knowledge in industry. For these properties, data was selected from less rigorous sources, such as blog posts and material datasheets.

**Table A1.** The selected design requirements, with corresponding structural and material properties, for plastic injection-moulded spare parts.

| Design Requirement | Structural Properties | Material Properties |
|---|---|---|
| *Geometry* | | |
| Shape | Size [2-7]<br>Wall thickness uniformity [3,6,8-11]<br>Undercuts/overhang [2-5,8-10,12-15]<br>Horizontal bridges [5,13]<br>Internal channels [4,12,14,16]<br>Part thickness/shell [9,11]<br>Feature spacing [10]<br>Pockets & cavities [6]<br>Draft angles (IM) [2,3,6,9,10,17] | Thermal expansion rate [1,18-22]<br>Linear mould shrinkage [19] |
| Detail | Minimum for<br>Bosses [3,6,8,9,11]<br>Ribs [3,8-11,15]<br>Gussets [3,8,9,11]<br>Radii [2,3,8,10,11]<br>Fillets [3,4,6,8-10,15,17]<br>Parting line (IM) [9,10]<br>Snapfits [3,9,15]<br>Minimum wall thickness [2-4,6,12-17]<br>Wall profiles [15]<br>Minimum feature size [4,5,12-16]<br>Pin diameter [5,6,13]<br>Supported wires [7]<br>Unsupported wires [7]<br>Supported walls [5,7,13]<br>Unsupported walls [5,7,13]<br>Embossed/engraved detail [4,5,7,13-17]<br>Text [4,6,9,14,15]<br>Holes [5,6,13-15,17]<br>Gaps [6,15,17] | Thermal expansion rate [1,18-22]<br>Linear mould shrinkage [19] |
| Accuracy and tolerances | Part tolerance [3,5,6,8,13,15,17]<br>Part clearance [5,7,13,14,16]<br>Maximum wall thickness [16]<br>Hollowing [4,14]<br>Surface area [6,13-15]<br>Interlocking/single-build assembly [4,14,16]<br>Minimum feature size [24]<br>Size [24] | Thermal expansion rate [1,18-22]<br>Linear mould shrinkage [19]<br>Material shrinkage [24] |

**Table A1.** The selected design requirements, with corresponding structural and material properties, for plastic injection-moulded spare parts. (continued)

| Design Requirement | Structural Properties | Material Properties |
|---|---|---|
| *Configuration* | | |
| Water-/ airtightness | Geometry complexity [14,25]<br>Wall thickness [25-27]<br>Surface finish [25-27]<br>IP-rating [28]<br>Interfaces [28]<br>Seal/gasket design [28]<br>Porosity/gaps [27] | Permeability ($O_2$/$CO_2$/$N_2$) [19] |
| | See also: Accuracy and Tolerances, Surface finish | |
| Multi-material | Inserts [9,29]<br>Fastening feature/mechanical bond [29]<br>Surface smoothness [29] | Material compatibility [29]<br>Material shrinkage [29]<br>Friction coefficient/surface roughness [29]<br>Wear resistance [29] |
| Surface finish | Surface finish [2-4,6,14-17,30]<br>Surface texture [30] | Friction coefficient [18]<br>Self-lubrication [18] |
| Transparency | Microstructure [1]<br>Wall thickness [1,31]<br>Surface finish [1,31,32]<br>Wall thickness uniformity [32]<br>Gradual transitions [32]<br>Release slope [32]<br>Geometry complexity [31] | Transparency [19,21]<br>Haze [33]<br>Luminous Transmittance [33]<br>Diffuse Transmittance [33]<br>Refractive index [1,19,33]<br>Absorption coefficient [1] |
| | See also: Surface finish | |
| *Mechanical requirements* | | |
| Strength | Microstructure [1]<br>Hardness [1]<br>Cross-sectional area [1]<br>Stress concentrators [1]<br>Part/feature size [14]<br>Wall thickness [14,34-36]<br>Maximum wall/section thickness [34,35]<br>Rib use [34-36]<br>Fillet/radii use [35,36]<br>Gusset use [34,36]<br>Transition smoothness [34] | Tensile strength [1,18-22,33,37-40]<br>Young's modulus [1,18-22,33,37-40]<br>Elongation at break [19-22,33,37-40]<br>Flexural strength [19,20,22,33,37,38]<br>Flexural modulus [19,20,22,33,37,38]<br>Specific strength [19]<br>Flexural Stress at 5% Strain [22]<br>Porosity [18] |
| Flexibility (bend) | Length [1]<br>Cross-sectional area [1]<br>Wall thickness [14,41]<br>Microstructure [41] | Young's modulus [1,18-22,33,37-40]<br>Flexural strength [19,20,22,33,37,38]<br>Flexural modulus [19,20,22,33,37,38]<br>Elongation at break [19-22,33,37-40]<br>Elongation at yield [19,21,38]<br>Shear modulus [1,18,19]<br>Hardness [20,22,33,38,42] |

**Table A1.** The selected design requirements, with corresponding structural and material properties, for plastic injection-moulded spare parts. (continued)

| Design Requirement | Structural Properties | Material Properties |
|---|---|---|
| Elasticity (stretch/ compress) | Length [1]<br>Cross-sectional area [1]<br>Microstructure [43] | Young's modulus [1,18-22,33,37-40]<br>Tensile strength [1,18-22,33,37-40]<br>Elongation at break [19-22,33,37-40]<br>Yield strength [1,18-22,38]<br>Hardness [1,18-22,33-40]<br>Material-specific stiffness [1,19]<br>Bulk modulus [1,18,19]<br>Compressive modulus [19]<br>Compressive strength [19]<br>Compression set [20,40]<br>Poisson's Ratio [1,19]<br>Elastic stored energy [19]<br>Resilience (Bayshore) [22,40,44]<br>Tear strength [20,22,40]<br>Stress at 50% elongation [22,40]<br>Stress at 100% elongation [22,40]<br>Stress at 150% elongation [40] |
| Impact resistance | Part geometry [45-47]<br>Corner radii [45,47,48]<br>Stress concentrators [45]<br>Notch size/radius & placement [45,48]<br>Hole size/radius & placement [45]<br>Fillet radius & use [45]<br>Rib use [45,46]<br>Wall thickness (optimization) [45,46,48]<br>Part shape/roundness [45]<br>Part feature/size and location [45]<br>Part thickness [46]<br>Part internal structure [48] | Fracture toughness [1,18,19]<br>Fracture strength [18]<br>Toughness [1,18,19,21]<br>Ductility index [19]<br>Impact strength notched [19,20,22,38,39]<br>Impact strength unnotched [19,22,38,39]<br>Impact strength (Izod, Charpy) [20,22]<br>Tear strength [20,22,40]<br>Flex fatigue (Ross) [22,40]<br>Resilience (Bayshore) [22,40,44]<br>Maximum Stress Intensity Factor ($K_{max}$) [39]<br>Work of Fracture ($W_f$) [39] |
| Abrasion resistance | Microstructure [1]<br>Surface roughness [1,49]<br>Contact area surface roughness [1,49]<br>Coating/surface treatment [49]<br>Lubrication [1,49] | Hardness [1,18-22,33-40]<br>Abrasion resistance (Tabor) [22]<br>Friction coefficient [1,18]<br>Archard wear constant [1,18]<br>(Specific) wear rate [1,18]<br>Self-lubrication [18] |
| | See also: Surface finish | |
| Fatigue resistance | Stress concentrators [1]<br>Compressive surface stress [1]<br>Surface finish/roughness [1]<br>Wall thickness [1] | Fracture toughness [1]<br>Fatigue limit/strength at $10^7$ cycles [18,19]<br>Fatigue endurance [18]<br>Yield strength [1,18,19,21,22,38]<br>Tensile strength [1,18-22,33,38]<br>Melting point [18,19]<br>Notch sensitivity [50]<br>Porosity [51]<br>Isotropy [51] |
| Creep resistance | Part geometry [52]<br>Stress concentrators [52]<br>Fillet/chamfer [52] | Creep resistance [18,20]<br>Glass temperature [1,50]<br>Maximum service temperature [1]<br>Creep modulus [1,50] |

**Table A1.** The selected design requirements, with corresponding structural and material properties, for plastic injection-moulded spare parts. (continued)

| Design Requirement | Structural Properties | Material Properties |
|---|---|---|
| *Thermal requirements* | | |
| Heat resistance | Part/feature thickness [1]<br>Part volume [1] | Melting temperature [1,18,19]<br>Glass transition temperature [1,18,19,21,22,33-39]<br>Ductile/brittle transition temperature [21,53]<br>Heat deflection temperature [19-22,33-39]<br>Vicat softening point [19,20,22]<br>Continuous service temperature [21]<br>Maximum service temperature [1,19,21]<br>Thermal conductivity [1,18,19,21]<br>Specific heat [1,18,19]<br>Heat capacity [1]<br>Thermal expansion coefficient [1,18-22,33,38,39]<br>Thermal shock resistance [1,18,19]<br>Thermal distortion resistance [19]<br>Thermal diffusivity [1,18]<br>Flammability [1,18,19,22,33-39] |
| Cold resistance | Part/feature thickness [1]<br>Part volume [1] | Ductile/brittle transition temperature [21,53]<br>Glass transition temperature [1,18,19,21,22,33-39]<br>Toughness at low temperature [21]<br>Continuous service temperature [21]<br>Minimum service temperature [1,18,19,21]<br>Thermal conductivity [1,18,19,21]<br>Specific heat [1,18,19]<br>Heat capacity [1]<br>Thermal expansion coefficient [1,18-22,33,38,39]<br>Thermal shock resistance [1,18,19]<br>Thermal distortion resistance [19]<br>Thermal diffusivity [1,18] |
| *Chemical requirements* | | |
| Water resistance | Crevices [1]<br>Wall thickness [27]<br>Porosity/gaps [27]<br>Surface finish [27] | Water absorption [19-22,38,39]<br>Water vapor transmission [19]<br>Permeability ($O_2$/$CO_2$/$N_2$) [19]<br>Humidity absorption [19]<br>Resistance to water [1,19] |
| | See also: Detail, Surface finish | |
| UV resistance | — | UV resistance [1,19,21]<br>Radiation absorption/dissipation factor [54]<br>Indoor stability [38]<br>Outdoor stability [38] |
| Chemical resistance | Crevices [1]<br>NEMA-rating [28] | Resistance to acids [1,19,22,39]<br>Resistance to alkalis [1,19,22,39]<br>Resistance to organic solvents [1,19,22,39]<br>Resistance to oxidation [1,19]<br>Resistance to radiation [1]<br>Resistance to fuels [1]<br>Resistance to oils [1]<br>Resistance to alcohols and aldehydes [1]<br>Chemical resistance index [19]<br>Environmental stress crack index [19]<br>Oxygen index [19] |
| | See also: Detail, Surface finish | |

**Table A1.** The selected design requirements, with corresponding structural and material properties, for plastic injection-moulded spare parts. (continued)

| Design Requirement | Structural Properties | Material Properties |
|---|---|---|
| Food safety | Surface finish [55,56]<br>Cleanability [55]<br>Crevices [55,56]<br>Ridges [55,56]<br>Corner radii [56]<br>Screw threads [56]<br>Dead zones [56]<br>Drainability [56]<br>Shaft passages and seals [56]<br>Porosity [56] | Food contact grade [19]<br>Sterilizability (ethylene oxide/radiation/ steam autoclave) [19,21,22,56]<br>Chemical resistance [56] |
| | See also: Detail, Surface finish, Chemical resistance | |

*[1] Ashby et al., (2014), [2] Protolabs, (2024a), [3] Xometry, (2024b), [4] Materialise, (2024c), [5] Xometry Pro, (2023b), [6] Xometry, (2024c), [7] Manuevo, (2024), [8] Xometry Pro, (2023a), [9] Geomiq, (2024), [10] SyBridge Technologies, (2021b), [11] Protolabs Network, (2024c), [12] Protolabs, (2024b), [13] Protolabs Network, (2024a), [14] Materialise, (2024b), [15] Xometry, (2024a), [16] Materialise, (2024a), [17] Xometry, (2024d), [18] Ashby, (1999), [19] ANSYS, (2023), [20] Formlabs, (2024), [21] Omnexus, (2024), [22] Formlabs, (2023), [23] Protolabs Network, (2024b), [24] Xometry Pro, (2023c), [25] Kočí, (2021), [26] Kočí, (2024), [27] UltiMaker (2024), [28] Brown (2022), [29] SyBridge Technologies (2021e), [30] ICOMold (2024), [31] SyBridge Technologies (2021b), [32] Zetar, (2022), [33] 3D Systems Inc. (2020), [34] Protolabs (2024a), [35] SyBridge Technologies (2021a), [36] Xometry Pro (2023b), [37] Senvol LLC (2024), [38] 3D Systems Inc. (2023), [39] Formlabs (2023a), [40] Formlabs (2023c), [41] BCN3D (2024), [42] Xometry Pro (2023d), [43] Schumacher et al. (2015), [44] Team Xometry, (2022), [45] Covestro (2016), [46] Rutland Plastics (2024), [47] SyBridge Technologies (2021d), [48] Plasticprop (2024), [49] Lee (2023), [50] Ashby & Jones (2012), [51] Seki et al. (2007), [52] SyBridge Technologies (2022), [53] Zeus Industrial Products Inc. (2005), [54] Ensinger (2024), [55] Directive 2006/42/EC, [56] Curiel (2003).*

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## 5.6 REFERENCES

3 Space (2019). *Injection Molding: Rib Design*. Retrieved May 13, 2024, from https://3space.com/injection-molding-rib-design/

3D Print Bureau (n.d.). *FDM Materials*. Retrieved June 18, 2024, from https://www.3dprintbureau.co.uk/materials/fdm-materials/

3D Systems (2016). *DuraForm ® TPU Elastomer*. Retrieved May 28, 2024, from https://www.3dsystems.com/sites/default/files/2017-02/3D-Systems_DuraForm_TPU_Elastomer_SLS_Datasheet_10.17.16_USA4_WEB.pdf

3D Systems (2018). *Accura ® 48HTR*. Retrieved October 16, 2024, from https://xometry.eu/wp-content/uploads/2020/08/Accura-48-PC-Heat-Specs.pdf

3D Systems (2022). *DuraForm ® PAx Natural*. https://www.3dsystems.com/sites/default/files/2022-10/3d-systems-duraform-pax-natural-sls-datasheet-usen-2022-07-13-a-print.pdf

3D Systems (2022). *DuraForm® PAx Black High*. https://www.3dsystems.com/sites/default/files/2022-09/3d-systems-duraform-pax-black-sls-datasheet-usen-2022-09-09-a-print.pdf

3D Systems (2023). *Accura® AMX™ High Temp 300C*. Retrieved October 16, 2024, from https://www.3dsystems.com/sites/default/files/2024-01/3d-systems-accura-high-temp-300c-datasheet-us-letter-2023-10-31_web.pdf

3D Systems (2023). *DuraForm PA11 Natural*. https://www.3dsystems.com/sites/default/files/2023-11/3d-systems-duraform-pa-11-natural-datasheet-us-a4-2023-10-31-a.pdf

3D Systems (n.d.). *DuraForm ® PA Plastic*. https://www.3dsystems.com/materials/duraform-pa/tech-specs

3D Systems (n.d.). *Selective Laser Sintering*. Retrieved June 11, 2024, from https://www.3dsystems.com/selective-laser-sintering

3D Systems Inc. (2020). *Accura® ClearVue™*. https://www.3dsystems.com/sites/default/files/2020-11/3d-systems-accura-clearvue-datasheet-us-a4-2020-09-15-a-print.pdf

3D Systems Inc. (2023). *Accura® AMX™ Tough FR V0 Black*. https://www.3dsystems.com/sites/default/files/2023-07/3d-systems-accura-tough-fr-v0-black-datasheet-usen-2023-07-26.pdf

3DPeople (n.d.). *PA12 Nylon (SLS).* Retrieved June 18, 2024, from https://www.3dpeople.uk/pa12-nylon-sls

3DPRINTUK (n.d.). *SLS Flexible TPU for Flexible, Rubber like Parts*. Retrieved June 6, 2024, from https://www.3dprint-uk.co.uk/flexible-rubber-like-material-for-3d-printed-parts/

3Dresyns (n.d.). *Detailed Guidelines to Select the Right 3D Resin for Your Needs*. Retrieved May 28, 2024, from https://www.3dresyns.com/pages/guidelines-to-select-the-right-3d-resin-for-your-needs

3faktur (n.d.). *The Surface Quality of Different 3D Printing Technologies*. Retrieved May 15, 2024, from https://3faktur.com/en/2017/05/26/the-surface-quality-of-different-3d-printing-technologies/

Abigail (2024). *Selective Laser Sintering (SLS) Materials Guide*. Retrieved June 18, 2024, from https://3dspro.com/resources/blog/selective-laser-sintering-materials-guide

Abtec (2019). *All You Need to Know About Injection Molded Thermoplastics.* Retrieved June 18, 2024, from https://www.abtecinc.com/news/injection-molded-thermoplastics/

ALM (n.d.). *HT-23.* Retrieved October 16, 2024, from https://www.advancedlasermaterials.com/wp-content/uploads/2023/01/HT-23-Data-Sheet-2022.pdf (accessed on 16 October 2024).

AMFG (2018). *TPU 3D Printing: A Guide to 3D Printing Flexible Parts*. Retrieved June 6, 2024 from https://amfg.ai/2018/07/23/tpu-3d-printing-guide/

ANSYS. (2023). *Granta Selector 2023 R2* (23.2.1). http://www.ansys.com/materials

Arceo, F. (2021) *Filaments and Moisture Absorption; Complete Guide!* Retrieved June 13, 2024, from https://3dsolved.com/filaments-and-moisture-absorption/

Ashby, M. F. (1999). *Materials Selection in Mechanical Design* (2nd ed.). Butterworth-Heinemann.

Ashby, M. F., & Jones, D. R. H. (2012). *Engineering materials 1 - An introduction to properties, applications, and design* (4th ed.). Butterworth-Heinemann.

Ashby, M., Shercliff, H., & Cebon, D. (2014). *Materials - Engineering, Science, Processing and Design* (3rd ed.). Butterworth-Heinemann. https://doi.org/978-0-08-097773-7

BASF (2021). *Ultrafuse TPU 64D (2).* Retrieved May 27, 2024, from https://forward-am.com/wp-content/uploads/2021/08/Ultrafuse_TPU_64D_TDS_EN_v1.1.pdf

BASF (2022). *Ultrasint ® PA6 MF Black*. Retrieved October 16, 2024, from https://move.forward-am.com/hubfs/PBF%20Documentation/PA6%20Line/PA6%20MF/BASF_3DPS_TDS_Ultrasint_PA6_MF_black.pdf

BASF 3D Printing Solutions GmbH (2022). *Ultrasint TPU 88A*. Retrieved June 6, 2024, from https://move.forward-am.com/hubfs/PBF%20Documentation/TPU%20Line/TPU%2088A%20Black/BASF_3DPS_TDS_Ultrasint-TPU-88A_Black_V1.pdf (accessed on 6 June 2024).

BASF 3D Printing Solutions GmbH (2023). *Ultrasint ® TPU 90A LT*. Retrieved June 6, 2024, from https://move.forward-am.com/hubfs/PBF%20Documentation/TPU%20Line/TPU%2090A%20LT/BASF_3DPS_ExtendedTDS_Ultrasint-TPU-90A%20LT.pdf

BCN3D (2020). Strongest 3D Printing Materials: Impact Resistant Filaments. Retrieved June 11, 2024, from https://www.bcn3d.com/strongest-3d-printing-materials-impact-fatigue-resistant-filaments/ (accessed on 11 June 2024).

BCN3D (2024). *How to stretch the flexibility of your parts even further.* https://support.bcn3d.com/knowledge/stretch-flexibility-parts

Behfard, S., Van Der Heijden, M. C., Al Hanbali, A., & Zijm, W. H. M. (2015). Last time buy and repair decisions for spare parts. *European Journal of Operational Research*, *244*(2), 498–510. https://doi.org/10.1016/j.ejor.2015.02.003

Beoplast (n.d.). *2C-Injection Moulding*. Retrieved May 14, 2024, from https://www.beoplast.de/en/our-compentences/2c-injection-moulding/ (accessed on 14 May 2024). Archived April 25, 2024, at https://web.archive.org/web/20240425022511/https://www.beoplast.de/en/our-compentences/2c-injection-moulding/

Billington, A (n.d.). Optimizing Strength of 3D Printed Parts. Retrieved June 11, 2024, from https://3dpros.com/guides/optimizing-part-strength

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

Bolaños Arriola, J., Van Oudheusden, A., Flipsen, B., & Faludi, J. (2022). 3D Printing for Repair Guide. In *3D Printing for Repair Guide*. https://doi.org/10.5074/t.2022.003

Brown, C. (2022). *Nothing Gets In: Waterproof Enclosure Design 101 (and IP68).* https://www.fictiv.com/articles/nothing-gets-in-waterproof-enclosure-design-101-and-ip68

Chen, Y. (2024). TPU vs TPE Filament: The Main Differences. Retrieved June 6, 2024, from https://all3dp.com/2/tpe-vs-tpu-flexible-filament-the-differences/

Choudhari, C. M., & Patil, V. D. (2016). Product Development and its Comparative Analysis by SLA, SLS and FDM Rapid Prototyping Processes. *IOP Conference Series: Materials Science and Engineering*, *149*(1). https://doi.org/10.1088/1757-899X/149/1/012009

Choudhari, C.M.; Patil, V.D. Product Development and Its Comparative Analysis by SLA, SLS and FDM Rapid Prototyping Processes. *IOP Conf. Ser. Mater. Sci. Eng.* **2016**, *149*, 012009. doi:10.1088/1757-899X/149/1/012009.

Cordella, M., Alfieri, F., & Sanfelix, J. (2019). *Analysis and development of a scoring system for repair and upgrade of products - Final report*. EUR 29711 EN, Publications Office of the European Union. https://doi.org/10.2760/725068

Covestro. (2016). *Enhancing Impact Resistance and Toughness in Molded Medical Parts*. Covestro Deutschland AG. https://solutions.covestro.com/-/media/covestro/solution-center/whitepapers/enhancing-impact-resistance-and-toughness-in-molded-medical-parts.pdf

Curiel, R. (2003). *Hygienic Design of Equipment in Food Processing*. FoodSafety Magazine. https://www.food-safety.com/articles/4350-hygienic-design-of-equipment-in-food-processing

Dassault Systèmes (n.d.). *SLA 3D Printing Materials Compared*. Retrieved February 29, 2024, from https://www.3ds.com/make/solutions/blog/sla-3d-printing-materials-compared

Directive 2006/42/EC. (n.d.). *Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006 on machinery, and amending Directive 95/16/EC (recast).*

DSM Functional Materials (2015). *Somos® WaterClear Ultra 10122*; Stratasys: Eden Prairie, MI, USA.

Ensinger (n.d.). *Chemical Resistant Plastics*. Retrieved June 12, 2024, from https://www.ensinger-plastics.com/en/plastic-material-selection/chemical-resistant

Ensinger (n.d.). *Plastics Good for Friction, Wear and Bearings*. Retrieved June 17, 2024, from https://www.ensingerplastics.com/en-us/shapes/plastic-material-selection/friction-wear

Ensinger (n.d.). *Plastics' Fitness for Use at Low Temperature*. Retrieved June 13, 2024, from https://www.ensingerplastics.com/en/plastic-material-selection/low-temperature

Ensinger. (2024). *Radiation resistant plastics.* https://www.ensingerplastics.com/en/plastic-material-selection/radiation-resistant

EOS (n.d.). *EOS TPU 1301*. Retrieved June 6, 2024, from https://www.eos.info/en-us/polymer-solutions/polymer-materials/data-sheets/mds-eos-tpu-1301?topdf

EOS (n.d.). *PA 2241 FR.* Retrieved October 16, 2024, from https://www.eos.info/en-us/polymer-solutions/polymer-materials/data-sheets/mds-pa-2241-fr?topdf

European Commission (2019). *The new ecodesign measures explained*. https://ec.europa.eu/commission/presscorner/detail/en/qanda_19_5889

European Parliament (2024). *Right to repair: Making repair easier and more appealing to consumers*. European Parliament. https://www.europarl.europa.eu/news/en/press-room/20240419IPR20590/right-to-repair-making-repair-easier-and-more-appealing-to-consumers

Faludi, J., Natasha, C.-T., & Shardul, A. (2017). 3D printing and its environmental implications. In *The Next Production Revolution Implications for Governments and Business*. OECD Publishing. https://doi.org/https://doi.org/10.1787/9789264271036-en

Fillamentum (n.d.). *Flexfill TPU Flexible Filament*. Retrieved May 27, 2024, from https://fillamentum.com/collections/flexfill-tpu-flexible-filament/

Flashforge (n.d.). *ABS Filament*. Retrieved June 13, 2024, from https://after-support.flashforge.jp/uploads/datasheet/tds/ABS_TDS_EN.pdf

Flashforge (n.d.). *ASA Filament*. Retrieved June 13, 2024, from https://after-support.flashforge.jp/uploads/datasheet/tds/ASA_TDS_EN.pdf

Forge Labs (2021). Can 3D Printing Produce Watertight Parts? Retrieved June 13, 2024, from https://forgelabs.com/blog/are-3d-printed-parts-watertight/

Forge Labs (n.d.). *Design Guide Selective Laser Sintering*. https://forgelabs.com/sls-design-guide/

Forge Labs (n.d.). *Stereolithography (SLA) 3D Printing Services*. Retrieved June 18, 2024, from https://forgelabs.com/stereolithography-sla/

Formero (2023). *How To Select The Right Material for SLS (Selective Laser Sintering)*. Retrieved June 11, 2024, from https://formero.com.au/blog/selecting-material-for-sls/

Formfutura (2015). Premium ABS. Retrieved June 13, 2024, from https://formfutura.com/datasheets/formfutura-tds-premiumabs.pdf. Archived July 6, 2024, at https://web.archive.org/web/20240706004816/https://www.formfutura.com/datasheets/formfutura-tds-premiumabs.pdf

Formfutura (n.d.). *Engineering SLA Resin–Tough*. Retrieved June 18, 2024, from https://formfutura.com/product/engineering-sla-series-tough-resin/

Formlabs (2019). *Elastic Resin: A Resilient, Soft, and Flexible 3D Printing Material*. Retrieved May 23, 2024, from https://formlabs.com/blog/elastic-resin-soft-resilient-3d-printing/

Formlabs (2020). *Engineering Fit: Optimizing Design for Functional 3D Printed Assemblies.* Formlabs: Somerville, MI, USA.

Formlabs (2020). Nylon 12 Powder. https://formlabs-media.formlabs.com/datasheets/2001447-TDS-ENUS-0.pdf (accessed on).

Formlabs (2020). *Rebound Resin: Production-Ready Elastic 3D Printing Material*. Retrieved June, 6, 2024, from https://formlabs-media.formlabs.com/datasheets/2001344-TDS-ENUS-0.pdf

Formlabs (2021). Nylon 11 Powder. https://formlabs-media.formlabs.com/datasheets/2101560-TDS-ENUS-0.pdf.

Formlabs (2022). Media Blasting to Improve Mechanical Properties of Rigid 10K Resin. Retrieved June 10, 2024, from https://formlabs.com/blog/media-blasting-engineering-materials/ (accessed on 10 June 2024).

FormLabs (2022). Nylon 12 GF Powder. Retrieved October 16, 2022, from https://formlabs-media.formlabs.com/datasheets/2201635-TDS-ENUS-0.pdf

Formlabs (2023*). 3D Printing Watertight Enclosures and Pressure Testing Results*. Retrieved April 16, 2024, from https://3d.formlabs.com/rs/060-UIG-504/images/WP-EN-3d-printing-watertight-enclosures-and-pressure-testing-results.pdf

Formlabs (2023). *Polypropylene Powder*. https://formlabs-media.formlabs.com/datasheets/2301856-TDS-ENUS-0.pdf

Formlabs (2023). *TPU 90A Powder*. Retrieved May 23, 2024, from https://formlabs-media.formlabs.com/datasheets/2301750-TPU-TDS-ENUS-0.pdf

Formlabs (2024). *Clear Resin*. Retrieved May 21, 2024, from https://formlabs-media.formlabs.com/datasheets/2401900-TDS-ENUS-0.pdf

Formlabs (2024). *How to Choose the Right 3D Printing Material*. https://formlabs.com/blog/how-to-choose-the-right-3D-printing-material/

Formlabs (n.d.) 3D Printing Materials: Engineering Resins. Retrieved June 10, 2024, from https://formlabs.com/materials/engineering/

Formlabs (n.d.) Heat-Resistant 3D Printing Materials Guide: Compare Processes, Materials, and Applications. Retrieved June 17, 2024, from https://formlabs.com/blog/heat-resistant-3d-printing/

Formlabs (n.d.). *10 Questions About Nylon 12 for the Fuse 1*. Retrieved June 17, 2024, from https://formlabs.com/blog/fuse-1-nylon-12-3d-printing-faq/

Formlabs (n.d.). *Flexible 3D Printing Guide: Compare Processes, Materials, and Applications*. Retrieved May 23, 2024, from https://formlabs.com/blog/flexible-3d-printing-materials-and-processes/

Formlabs (n.d.). Guide to 3D Printing Materials: Types, Applications, and Properties. Retrieved May 7, 2024, from https://formlabs.com/blog/3d-printing-materials/

Formlabs (n.d.). *Guide to Post-Processing and Finishing SLA Resin 3D Prints*. Retrieved June 10, 2024, from https://formlabs.com/blog/post-processing-and-finishing-sla-prints/ (accessed on 10 June 2024).

Formlabs (n.d.). *Guide to Selective Laser Sintering (SLS) 3D Printing*. Retrieved from https://3d.formlabs.com/rs/060-UIG-504/images/WP-EN-Guide-to-Selective-Laser-Sintering-SLS-3D-Printing.pdf?

Formlabs (n.d.). *Guide to Stereolithography (SLA) 3D Printing*. Retrieved May 1, 2024, from https://formlabs.com/eu/blog/ultimate-guide-to-stereolithography-sla-3d-printing/

Formlabs (n.d.). *Guide to Transparent 3D Printing*. Retrieved May 21, 2024, from https://formlabs.com/eu/blog/3d-printing-transparent-parts-techniques-for-finishing-clear-resin/

Formlabs (n.d.). *Nylon 3D Printing Guide: Compare Processes, Materials, and Applications*. Retrieved from https://formlabs.com/blog/nylon-3d-printing/

Formlabs (n.d.). *Overmolding and Insert Molding: From Prototyping to Production.* Retrieved May 15, 2024, from https://formlabs.com/blog/overmolding-insert-molding/

Formlabs (n.d.). *SLS Powders*. Retrieved June 21, 2024, from https://formlabs.com/materials/sls-powders/. Archived September 13, 2024, at https://web.archive.org/web/20240913013548/https://formlabs.com/materials/sls-powders/

Formlabs (n.d.). *Solvent Compatibility*. Retrieved June 12, 2024, from https://support.formlabs.com/s/article/Solvent-Compatibility?language=en_US

Formlabs (n.d.). Speci*alty Resins: Functional Materials with Specialized Properties*. Retrieved June 13, 2024, from https://formlabs.com/materials/engineering/specialty/

Formlabs (n.d.). *The Essential Guide to Food Safe 3D Printing: Regulations, Technologies, Materials, and More*. Retrieved June 11, 2024, from https://formlabs.com/blog/guide-to-food-safe-3d-printing/ (accessed on 11 June 2024).

Formlabs (n.d.). *Using Durable Resin*. Retrieved June 17, 2024, from https://support.formlabs.com/s/article/Using-Durable-Resin?language=en_US (accessed on 17 June 2024).

Formlabs (n.d.). *Validating Isotropy in SLA 3D Printing*. Retrieved May 14, 2024, from https://formlabs.com/blog/isotropy-in-SLA-3D-printing/

Formlabs. (2023a). *Flame Retardant*. https://formlabs-media.formlabs.com/datasheets/2301761-TDS-ENUS-0.pdf

Formlabs. (2023b). *Materials Library.* https://formlabs-media.formlabs.com/datasheets/1901266-TDS-ENUS-0.pdf

Formlabs. (2023c). *Silicone 40A*. Formlabs. https://formlabs-media.formlabs.com/datasheets/2301817-TDS-ENUS-0.pdf

Geomiq (2024). *Injection Moulding Design Guide*. https://geomiq.com/injection-moulding-design-guide/

GKN Additive (Forecast 3D) (n.d.). *FDM Materials*. Retrieved June 11, 2024, from https://www.forecast3d.com/materials/fdm (accessed on 11 June 2024).

GKN Additive (Forecast 3D) (n.d.). *SLA Materials*. Retrieved June 13, 2024, from https://www.forecast3d.com/materials/sla (accessed on 13 June 2024).

Grimm, M. (n.d.). *Durability of Photopolymers in 3D Printing*. Retrieved June 12, 2024, from https://www.jellypipe.com/en/blog-news/durability-of-photopolymers-in-3d-printing

Groupe PolyAlto (n.d.). *The Wear Resistance of Plastics*. Retrieved June 17, 2024, from https://blogue.polyalto.com/en/the-wear-resistance-of-plastics

Hertz, J. (2023). *New Technique Enables Intermixing Materials in SLA 3D Printing*. Retrieved May 14, 2024, from https://3dprint.com/301106/new-technique-enables-intermixing-materials-in-sla-3d-printing/.

Hogan, M. (2023). *Clear Resin 3D Printing: How to 3D Print Transparent Resin Parts*. Retrieved May 21, 2024, from https://nexa3d.com/blog/clear-resin-3d-printing/. Archived October 23, 2024, at https://web.archive.org/web/20241023194646/https://nexa3d.com/blog/clear-resin-3d-printing/

Hogan, M. (2023). *Types & Benefits of SLS Materials for 3D Printing*. Retrieved from https://nexa3d.com/blog/sls-materials/ (accessed on 2 July 2024). Archived October 23, 2024, at https://web.archive.org/web/20241023194638/https://nexa3d.com/blog/sls-materials/

Holmström, J., & Gutowski, T. (2017). Additive Manufacturing in Operations and Supply Chain Management: No Sustainability Benefit or Virtuous Knock-On Opportunities? *Journal of Industrial Ecology*, *21*, S21–S24. https://doi.org/10.1111/jiec.12580

Huryn, A. (2022). *What Is Injection Molding and Several Features vs. 3D Printing*. Retrieved May 14, 2024, from https://www.linkedin.com/pulse/what-injection-molding-several-features-vs-3d-printing-anton-huryn

ICOMold. (2024). *Plastic Injection Molded Parts – Surface Finishes*. ICOMold by Fathom. https://icomold.com/surface-finishes/

Ignacio, J. (2023). *Injection Molded Plastics and Elastomers*. Retrieved June 12, 2024, from https://community.xometry.com/kb/articles/794-injection-molded-plastics-and-elastomers

Ignacio, J. (2023). *Which 3D Printing Processes Are Watertight?* Retrieved April 16, 2024, from https://community.xometry.com/kb/articles/759-which-3d-printing-processes-are-watertight

Igus (n.d.). *3D Printing Filament*. Retrieved June 18, 2024, from https://www.igus.com/3d-print-material/3d-print-filament (accessed on 18 June 2024).

igus (n.d.). *Iglide® I190-PF 3D Print Filament*. Retrieved June 18, 2024, from https://www.igus.com/product/20322?artNr=I190-PF-0300-0750

Igus (n.d.). *Iglide® I3-PL, SLS Powder.* Retrieved June 18, 2024, from https://www.igus.com/product/719?artNr=I3-PL-10000 (accessed on 18 June 2024).

Igus (n.d.). Iglide® I6-PL, Laser Sintering Material. Retrieved June 18, 2024, from https://www.igus.com/product/14950?artNr=I6-PL-10000

INFINAM (n.d.). *INFINAM TPA 4006 P*. Retrieved May 28, 2024, from https://www.infinam.com/en/3d-printing-materials/polymer-powders/thermoplastic-amides

INFINAM *Infinam® TPC 8008 P*. Retrieved May 28, 2024, from https://www.infinam.com/en/3d-printing-materials/polymer-powders/thermoplastic-elastomers. Archived June 25, 2024, at https://web.archive.org/web/20240625151557/https://www.infinam.com/en/3d-printing-materials/polymer-powders/thermoplastic-elastomers

Integrated Molding Solutions (n.d.). *Injection Molding Materials Selection Guide*. Retrieved May 23, 2024, from https://ims-tex.com/injection-molding-materials-selection-guide/

JLCPCB (n.d.). *What Is Stereolithography (SLA) 3D Printing*. Retrieved July 23, 2024, from https://jlcpcb.com/help/article/363-what-is-sla-3d-printing

Jung, S., Kara, L. B., Nie, Z., Simpson, T. W., & Whitefoot, K. S. (2023). Is Additive Manufacturing an Environmentally and Economically Preferred Alternative for Mass Production? *Environmental Science and Technology*, *57*(16), 6373–6386. https://doi.org/10.1021/acs.est.2c04927

Karania, R., & Kazmer, D. (2007). Low Volume Plastics Manufacturing Strategies. *Journal of Mechanical Design*, *129*(12), 1225–1233. https://doi.org/10.1115/1.2790978

King, A. M., Burgess, S. C., Ijomah, W., & McMahon, C. A. (2006). Reducing waste: Repair, recondition, remanufacture or recycle? *Sustainable Development*, *14*(4), 257–267. https://doi.org/10.1002/sd.271

Knofius, N., van der Heijden, M. C., & Zijm, W. H. M. (2019). Consolidating spare parts for asset maintenance with additive manufacturing. *International Journal of Production Economics*, *208*(October 2018), 269–280. https://doi.org/10.1016/j.ijpe.2018.11.007

Kočí, J. (2021). *Watertight 3D printing PT1: Vases, cups and other open models*. Prusa Research a.s. https://blog.prusa3d.com/watertight-3d-printing-pt1-vases-cups-and-other-open-models_48949/

Kočí, J. (2024). *Watertight 3D printing part 2: Airtight closable models*. Prusa Research a.s. https://blog.prusa3d.com/watertight-3d-printing-part-2_53638/

Kwon, N.; Deshpande, H.; Hasan, M.K.; Darnal, A.; Kim, J. *Multi-Ttach: Techniques to Enhance Multi-Material Attachments in Low-Cost FDM 3D Printing*; Association for Computing Machinery: New York, NY, USA, 2021; Volume 1; ISBN 9781450390903.

Lau, J. (2019) *Surface Finish of Plastic Injection Molding Product*. Retrieved May 15, 2024, from https://www.ecomolding.com/surface-finish/. Archived July 23, 2024, at https://web.archive.org/web/20240723031044/https://www.ecomolding.com/surface-finish/

Lau, J. (2020). *Transparent(Clear) Plastic Materials' Characteristics & Injection Molding Process*. Retrieved May 21, 2024, from https://www.ecomolding.com/transparent-plastic-materials/. Archived May 20, 2024, at https://web.archive.org/web/20240520221649/https://www.ecomolding.com/transparent-plastic-materials/

Lee, J. (2023). *3 Tips to Help You Design for Wear Resistance and High Wear Applications*. Gensun Precision Machining Co., Limited. https://www.china-machining.com/blog/design-for-wear-resistance/

Liqcreate (n.d.). *3D-Printed Strong-X Resin Part in Freezing Conditions*. Retrieved June 13, 2024, from https://www.liqcreate.com/supportarticles/performance-of-3d-printed-strong-x-resin-parts-in-freezing-conditions/

Liqcreate (n.d.). *Chemical Resistant and Chemical Compatible 3D-Print Resin*. Retrieved June 12, 2024 from https://www.liqcreate.com/supportarticles/chemical-compatibility-of-3d-printed-resin-parts/

Liqcreate (n.d.). *Mixing 3D-Printing Resins: Properties and 3D-Printing Behavior*. Retrieved May 14, 2024, from https://www.liqcreate.com/supportarticles/mixing-3d-printing-resins-properties-and-3d-printing-behavior/

Liqcreate (n.d.). *UV Aging of 3D-Printing Resin Tested by Eindhoven University*. Retrieved June 12, 2024, from https://www.liqcreate.com/supportarticles/uv-aging-of-3d-printing-resin-tested-by-eindhoven-university/

Liqcreate (n.d*.). Waterproof & Airtight Resin 3D-Printed Parts*. Retrieved May 14, 2024, from https://www.liqcreate.com/supportarticles/waterproof-airtight-resin-3dprinted-part/

Luvosint (n.d.). *LUVOSINT ® TPU X92A-1 NT Thermoplastic Polyurethane*. Retrieved June 6, 2024, from https://www.lehvoss.de/en/Compounds/products/3d-printing-materials/luvosint (accessed on 6 June 2024).

Manuevo (2024). *Design Guidelines-PA12 Nylon (SLS).* https://manuevo.com/wp-content/uploads/2024/08/Design-Guidelines-manuevo-PA12-Nylon.pdf

Materialise (2024). Datasheets 3D Printing Materials Selective Laser Sintering. Retrieved from https://assets-eu-01.kc-usercontent.com/8ff24b0e-57a3-0157-62d1-fa4ac9734eb5/edcc4c15-f708-4a47-94c3-41c547b928d0/materialise-datasheets-laser-sintering.pdf

Materialise (2024a). *Design Guidelines for ABS | Fused Deposition Modeling*. https://www.materialise.com/en/academy/industrial/design-am/abs

Materialise (2024b). *Design Guidelines for PA 12 (SLS) | Laser Sintering*. https://www.materialise.com/en/academy/industrial/design-am/pa12-sls

Materialise (2024c). *Design Guidelines for Poly1500 | Stereolithography*. https://www.materialise.com/en/academy/industrial/design-am/poly1500

Melito, S. (2023). *The Top Five UV Resistant Plastics for Part Designers*. Retrieved June 12, 2024, from https://www.fictiv.com/articles/the-top-five-uv-resistant-plastics-for-part-designers

Mitsubishi Chemical Group (n.d.). *Low Friction and Wear Resistance in Engineering Plastics*. Retrieved June 17, 2024, from https://www.mcam.com/en/support/material-properties/wear-resistance

Morocz, Y. (n.d.). Compatibility of FDM Polymers at Multi-Material Interfaces. Retrieved May 15, 2024, from https://static1.squarespace.com/static/5ab922b89f8770e76e7eded5/t/65c396f106c4b922514d20bf/1713908729893/Multi_Material_FDM_Compatibility.pdf

NASA (n.d.). 3D-Printed Composites for High Temperature Uses (LEW-TOPS-145). Retrieved June 18, 2024, from https://technology.nasa.gov/patent/LEW-TOPS-145. Archived June 15, 2024, at https://web.archive.org/web/20240615001029/https://technology.nasa.gov/patent/LEW-TOPS-145

NinjaTek (2021). *Chinchilla ™ 3D Printing Filament*. Retrieved June 6, 2024, from https://ninjatek.com/wp-content/uploads/Chinchilla-TDS.pdf

Nutma, M. (2019). *A Quick Guide to Dimensional Accuracy for 3D Printing*. Retrieved May 14, 2024, from https://www.voxelmatters.com/quick-guide-dimensional-accuracy-3d-printing/ (accessed on 14 May 2024).

O'Connell, J. (2024). *How to Make Waterproof 3D Prints*. Retrieved June 13, 2024, from https://all3dp.com/2/waterproof-3d-print-pla/

Oceanz (n.d.). *EC 1935/2004–Food Grade 3D Printing*. Retrieved June 11, 2024, from https://www.oceanz.eu/en/food-grade-3d-printing-ec1935-2004/. Archived June 18, 2024, at https://web.archive.org/web/20240618224423/https://www.oceanz.eu/en/food-grade-3d-printing-ec1935-2004/

Oceanz B.V. (n.d.). *Features and Facts about the SLS Technology.* Retrieved May 13, 2024, from https://www.oceanz.eu/blog/features-and-facts-about-the-sls-technology/ (accessed on 13 May 2024). Archived June 18, 2024, at https://web.archive.org/web/20240618205006/https://www.oceanz.eu/blog/features-and-facts-about-the-sls-technology/

Odedairo, B. O. (2021). Managing Spare Parts Inventory by Incorporating Holding Costs and Storage Constraints. *Journal of Engineering, Project, and Production Management*, *11*(2), 139–144. https://doi.org/10.2478/jeppm-2021-0014

Omnexus (2024). *Polymer Properties & Chemical Resistance of Plastics*. SpecialChem. https://omnexus.specialchem.com/polymer-properties

Osborne Industries (2019). *Low-Friction & Abrasion Resistant Plastics*. Retrieved June 17, 2024, from https://www.osborneindustries.com/news/low-friction-abrasion-resistant-plastics/ (accessed on 17 June 2024).

Pérès, F., & Noyes, D. (2006). Envisioning e-logistics developments: Making spare parts in situ and on demand. State of the art and guidelines for future developments. *Computers in Industry*, *57*(6), 490–503. https://doi.org/10.1016/j.compind.2006.02.010

Philips (n.d.). *SpeedPro*. Retrieved July 29, 2024, from https://www.philips.nl/c-p/FC6723_01/speedpro (accessed on 29 July 2024). Archived June 23, 2024, at https://web.archive.org/web/20240623040339/https://www.philips.nl/c-p/FC6723_01/speedpro/

Piedra-Cascón, W.; Sadeghpour, M.; Att, W.; Revilla-León, M. A Vat-Polymerized 3-Dimensionally Printed Dual-Material Occlusal Device: A Dental Technique. *J. Prosthet. Dent.* **2021**, *126*, 271–275. https://doi.org/10.1016/j.prosdent.2020.07.011.

Plasticprop (2024). *Plastic products and Impact Resistance*. https://www.plasticprop.com/articles/impact-resistance/

Plastics Plus (n.d.). *Technology Plastic Finishes and Textures*. Retrieved May 15, 2024, from https://www.plasticsplus.com/wp-content/uploads/2021/01/Plastic-Finishes-and-Textures-1.pdf

Prior, M. (2022). *Multi-Material SLS 3D Printing: A Reality Thanks to Sharebot?* Retrieved April 16, 2024, from https://www.3dnatives.com/en/multi-material-sls-3d-printing-sharebot-170320225/ (accessed on 16 April 2024).

Prior, M. (2024). *All You Need to Know About Multi-Material 3D Printing*. Retrieved May 15, 2024, from https://www.3dnatives.com/en/all-you-need-to-know-about-multi-material-3d-printing-220120245/

Productive Plastics Inc. (2018). *Choosing Between Injection Molding vs. Plastic Thermoforming: Part Size Has a Big Impact*. Retrieved May 1, 2024, from https://www.productiveplastics.com/part-size-is-a-big-factor-on-injection-molding-vs-plastic-thermoforming-productive-plastics/ (accessed on 1 May 2024).

Prodways (2022). *TPU-70A*. Retrieved May 28, 2024, from https://www.prodways.com/wp-content/uploads/2016/04/202112-Datasheet-TPU-70A.pdf

Proto Labs (2016). *Materials Matter: The Material Selection Process*. Retrieved June 13, 2024, from https://www.protolabs.com/media/751799/materials-matter_wp_uk.pdf

Protolabs (2021). *Materials Matter : Selecting the Right Material for 3D Printing*. Retrieved May 22, 2024, from https://www.protolabs.com/en-gb/resources/guides-and-trend-reports/selecting-the-right-material-for-3d-printing/

Protolabs (2022). *The Advantages and Disadvantages of Glass-Filled Nylon*. Retrieved June 17, 2024, from https://www.protolabs.com/resources/blog/the-advantages-and-disadvantages-of-glass-filled-nylon/

Protolabs (2022). *Translucent and Clear Plastic Injection-Molded Parts*. Retrieved April 16, 2024, from https://www.protolabs.com/resources/blog/translucent-and-clear-plastic-injection-molded-parts/

Protolabs (2023). *Advantages and Disadvantages of Selective Laser Sintering*. Retrieved June 11, 2024 from https://www.protolabs.com/resources/blog/advantages-and-disadvantages-of-selective-laser-sintering/

Protolabs (2024). *3D Printing-Surface Finishes: Selective Laser Sintering*; Version 1; Proto Labs GmbH: Putzbrunn, Germany.

Protolabs (2024). *Selective Laser Sintering (SLS) What Is the Best Material for My Project?* Retrieved June 12, 2024, from https://www.protolabs.com/en-gb/resources/blog/selective-laser-sintering-sls-what-is-the-best-material-for-my-project/

Protolabs (2024a). *Design Essentials for Injection Moulding*. Proto Labs Ltd. https://www.protolabs.com/en-gb/resources/design-tips/design-essentials-for-injection-moulding/

Protolabs (2024b). *Design Guidelines: Plastic Injection Molding*. Proto Labs Ltd. https://www.protolabs.com/services/injection-molding/plastic-injection-molding/design-guidelines/

Protolabs (2024c). *What is Design for Additive Manufacturing?* Proto Labs Ltd. https://www.protolabs.com/resources/guides-and-trend-reports/what-is-design-for-additive-manufacturing/

Protolabs (n.d.). *5 Ways to Master Complex Features in Injection-Moulded Parts*. Retrieved May 14, 2024, from https://www.protolabs.com/en-gb/resources/design-tips/5-ways-to-master-complex-features-in-injection-moulded-parts/

Protolabs (n.d.). *A Guide to Stereolithography 3D Printing Materials*. Retrieved June 13, 2024, from https://www.protolabs.com/resources/design-tips/a-guide-to-stereolithography-3d-printing-materials/ (accessed on 13 June 2024).

Protolabs (n.d.). *Common Impact-Resistant Plastics*. Retrieved June 10, 2024, from https://www.protolabs.com/en-gb/resources/design-tips/common-impact-resistant-plastics/ (accessed on 10 June 2024).

Protolabs (n.d.). *Evaluating UV-Resistant Plastic Options*. Retrieved June 12, 2024, from https://www.protolabs.com/en-gb/resources/design-tips/uv-resistant-plastics/

Protolabs (n.d.). *How to Reinforce Parts with Support Features and Durable Materials*. Retrieved May 22, 2024, from https://www.protolabs.com/en-gb/resources/design-tips/adding-strength-to-injection-moulded-parts/

Protolabs (n.d.). *Liquid Silicone Rubber Takes the Heat*. Retrieved June 11, 2024, from https://www.protolabs.com/en-gb/resources/guides-and-trend-reports/liquid-silicone-rubber-takes-the-heat/

Protolabs (n.d.). *Redefining Surface Quality 3D Printed Parts*. Retrieved May 14, 2024, from https://www.protolabs.com/en-gb/services/3d-printing/enhanced-surface-quality-for-sls-and-mjf-parts/

Protolabs (n.d.). SLS Materials. Retrieved June 18, 2024, from https://www.protolabs.com/en-gb/resources/insight/sls-materials/

Protolabs (n.d.). *What Is Selective Laser Sintering (SLS)?* Retrieved May 15, 2024, from https://www.protolabs.com/resources/design-tips/designing-for-selective-laser-sintering/

Protolabs Network (2024a). *Design Rules for 3D Printing*. 3D HUBS B.V. https://www.hubs.com/get/3d-printing-design-rules/

Protolabs Network (2024b). *How to design parts for FDM 3D printing*. 3D HUBS B.V. https://www.hubs.com/knowledge-base/how-design-parts-fdm-3d-printing/

Protolabs Network (2024c). *How to design parts for SLA 3D printing*. 3D HUBS B.V. https://www.hubs.com/knowledge-base/how-design-parts-sla-3d-printing/

Protolabs Network (n.d.). *How Do You Design Snap-Fit Joints for 3D Printing?* Retrieved July 2, 2024, from https://www.hubs.com/knowledge-base/how-design-snap-fit-joints-3d-printing/

Protolabs Network (n.d.). *How to Design Parts for SLS 3D Printing*. Retrieved May 13, 2024, from https://www.hubs.com/knowledge-base/how-design-parts-sls-3d-printing/

Protolabs Network (n.d.). *Injection Molding: The Manufacturing & Design Guide*. Retrieved April 29, 2024, from https://www.hubs.com/guides/injection-molding/

Protolabs Network (n.d.). *PA 12*. Retrieved May 22, 2024, from https://www.hubs.com/3d-printing/plastic/nylon/sls-standard-nylon/

Protolabs Network (n.d.). *What Are the Optimal Shell and Infill Parameters for FDM 3D Printing?* Retrieved February 29, 2024, from https://www.hubs.com/knowledge-base/selecting-optimal-shell-and-infill-parameters-fdm-3d-printing/

Protolabs Network (n.d.). *What Is FDM (Fused Deposition Modeling) 3D Printing?* Retrieved May 13, 2024, from https://www.hubs.com/knowledge-base/what-is-fdm-3d-printing/

Protolabs Network (n.d.). *What Is SLA Printing? The Original Resin 3D Print Method*. Retrieved May 22, 2024, from https://www.hubs.com/knowledge-base/what-is-sla-3d-printing/#what-are-the-characteristics-of-sla-3d-printing

Protolabs Network (n.d.). *What Is SLS 3D Printing?* Retrieved February 22, 2024, from https://www.hubs.com/knowledge-base/what-is-sls-3d-printing/

Protolabs Network (n.d.). *What's the Ideal Filament for FDM 3D Printing? 3D Printing Materials Compared*. Retrieved June 18, 2024, from https://www.hubs.com/knowledge-base/fdm-3d-printing-materials-compared/

Protolabs Network (n.d.). *What's the Right Resin for SLA? 3D Printing Materials Compared*. Retrieved April 30, 2024, from https://www.hubs.com/knowledge-base/sla-3d-printing-materials-compared/

Prusa Polymers Team (2021). *Chemical Resistance of 3D Printing Materials*. Retrieved June 1, 2022, from https://prusament.com/chemical-resistance-of-3d-printing-materials/

Prusa Research (n.d.). Prusa Material Table. Retrieved from https://help.prusa3d.com/materials (accessed on 27 May 2024).

RapidDirect (2022). *Two-Shot Molding vs. Overmolding: What Are Their Differences?* Retrieved May 15, 2024, from https://www.rapiddirect.com/blog/two-shot-molding-vs-injection-molding/ (accessed on 15 May 2024).

Recreus (2018). *FILAFLEX 60A "PRO"*. Retrieved June 10, 2024, from https://drive.google.com/file/d/1qmdbzEL1n_vNzYAzxeeiFaso8lZyAr31/view

Recreus (2021). *FILAFLEX 82A ORIGINAL*. Retrieved June 10, 2024, from https://drive.google.com/file/d/1OwRPmpMaV8Uc1xceKfu-E4-6PJ74vGHo/view

Recreus (2022). FILAFLEX 95A MEDIUM-FLEX. Retrieved June 10, 2024, from https://drive.google.com/file/d/1OSyEnpjHmDkPFHPhyAD7RIjoZsHShiwG/view

Recreus (2023). *FILAFLEX 70A ULTRA-SOFT*. Retrieved June 10, 2024, from https://drive.google.com/file/d/1YSBebMexZTB5hdxO_csrRzLt5_MefwnW/view

ROMIRA (2019). Rotec ASA S 510. Retrieved June 13, 2024, from https://www.romira.de/fileadmin/user_upload/TDS_ROTEC_ASA_S_510.pdf

Rutland Plastics (2024). *Impact Strength*. Rutland Plastics. https://www.rutlandplastics.co.uk/design-guidelines/impact-strength/

Šajn, N. (2022). *Right to Repair*. European Parliamentary Research Service. https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/698869/EPRS_BRI(2022)698869_EN.pdf

Salmi, M., & Pei, E. (2023). Additive manufacturing processes and materials for spare parts. *Journal of Mechanical Science and Technology*, *37*(11), 5979–5990. https://doi.org/10.1007/s12206-023-1034-0

Schadegg, J. Stereolithography (SLA) 3D Printed Materials. Retrieved from https://community.xometry.com/kb/articles/792-stereolithography-sla-3d-printed-materials (accessed on 18 June 2024).

Schumacher, C., Bickel, B., Rys, J., Marschner, S., Daraio, C., & Gross, M. (2015). Microstructures to control elasticity in 3D printing. *ACM Trans. Graph.*, *34*(4). https://doi.org/10.1145/2766926

Scott, K. A., & Weaver, S. T. (2014). To Repair or Not to Repair: What is the Motivation? *Journal of Research for Consumers*, *January 2014*, 1–31.

Sculpteo (2020). *The Complete Surface Finish Guide For 3D Printing*. Retrieved May 15, 2024, from https://info.sculpteo.com/hubfs/downloads/The%20Complete%20Surface%20Finish%20Guide%20For%203D%20Printing.pdf

Seki, H., Tane, M., Otsuka, M., & Nakajima, H. (2007). Effects of pore morphology on fatigue strength and fracture surface of lotus-type porous copper. *Journal of Materials Research*, *22*(5), 1331–1338. https://doi.org/10.1557/jmr.2007.0164

Senvol LLC (2024). *Senvol Database*. http://senvol.com/5_material-results/

Shapeways (n.d.). *The Expert Guide to Nylon Plastics*. Retrieved from https://www.shapeways.com/blog/nylon-plastics-material-guide-pa11-pa12-pa12gb-sls-mjf (accessed on 27 June 2024). Archived July 7, 2024, at https://web.archive.org/web/20240707033640/https://www.shapeways.com/blog/nylon-plastics-material-guide-pa11-pa12-pa12gb-sls-mjf

Simplify3D (n.d.). *Filament Properties Table*. Retrieved April 30, 2024, from https://www.simplify3d.com/resources/materials-guide/properties-table/

Simplify3D (n.d.). *Ultimate 3D Printing Materials Guide*. Retrieved June 18, 2024, from https://www.simplify3d.com/resources/materials-guide/

Singh, R., Singh, S., Singh, I. P., Fabbrocino, F., & Fraternali, F. (2017). Investigation for surface finish improvement of FDM parts by vapor smoothing process. *Composites Part B: Engineering*, *111*, 228–234. https://doi.org/10.1016/j.compositesb.2016.11.062

Singh, R.; Singh, S.; Singh, I.P.; Fabbrocino, F.; Fraternali, F. Investigation for Surface Finish Improvement of FDM Parts by Vapor Smoothing Process. *Compos. B Eng.* **2017**, *111*, 228–234, doi:10.1016/j.compositesb.2016.11.062.

Sinterit (2019). *SLS 3D Printing Powders Widest Offer for Compact SLS Print Whatever You Want*. Retrieved May 23, 2024, from https://sls3d.de/wp-content/uploads/Sinterit_folder_Powders_11-2019-EN-spread-1.pdf

Skar Precision Mouldings (2013). *Minimum Wall Thickness for Injection Moulding*. Retrieved May 13, 2024, from https://skar.co.uk/wall-thickness-for-injection-moulding/

SpecialChem SA (2024). *Water Absorption 24 Hours*. Retrieved June 13, 2024, from https://omnexus.specialchem.com/polymer-property/water-absorption-24-hours

Spectroplast (n.d.). *TrueSil Portfolio*. Retrieved May 23, 2024, from https://spectroplast.com/materials/truesil/

Stahel, W. R. (2010). *The Performance Economy* (P. Macmillan, Ed.; 2nd ed.).

Stratasys (2017). *ABSi*. Retrieved October 16, 2024, from https://stratasysstorage01.file.core.windows.net/portal10-files-prod/1c1af60a-d02e-489e-92a2-72c2b920ec9b/ABSi-P500%20-%20EN%20FDM%20Material%20Datasheet.pdf?sv=2023-01-03&st=2025-08-31T13%3A08%3A08Z&se=2025-09-01T19%3A08%3A08Z&sr=f&sp=r&rscd=inline%3B+filename%3D%22ABSi-P500+-+EN+FDM+Material+Datasheet.pdf%22&rsce=UTF-8&rsct=application%2Fpdf&sig=bQcnEfizTjX0meTrzL2Cmy1xPgrUkfMcYQG5RZxVFGc%3D

Stratasys (2017). *ABSplus-P430*. Retrieved May 22, 2024, from https://assets.ctfassets.net/q2hzfkp3j57e/a653eccea038a0dddbf5e1d2c5dd990e9f244131d925042abb49489766ebcfdd/0f5d34bc026735510fa0e48c0d605387/c83d5d72-4c82-45d3-ab4a-fddfd1bc37b0_datasheets-stratasys-abs-plus.pdf

Stratasys (2017). *PPSF*. Retrieved October 16, 2024, from https://www.stratasys.com/siteassets/materials/materials-catalog/fdm-materials/ppsf/mss_fdm_fortusppsf_1117a.pdf?v=48dd51

Stratasys (2018). *FDM Materials Chemical Compatibility*. https://forerunner3d.com/wp-content/uploads/2019/12/MDS_FDM_MaterialsChemicalCompatibility_0918a.pdf. Archived October 25, 2024 at https://web.archive.org/web/20231109060330/https://forerunner3d.com/wp-content/uploads/2019/12/MDS_FDM_MaterialsChemicalCompatibility_0918a.pdf

Stratasys (2018). *FDM TPU 92A*. Retrieved from https://www.stratasys.com/siteassets/materials/materials-catalog/fdm-materials/tpu-92a/fdm-tpu-92a-3d-printing-material-data-sheet_a.pdf (accessed on 27 May 2024).

Stratasys (2018). *Top 4 Differences Between Stereolithography and PolyJet*. Retrieved June 12, 2024, from https://www.stratasys.com/en/stratasysdirect/resources/articles/differences-between-stereolithography-polyjet/

Stratasys (2020). *PC-ISO*. Retrieved October 16, 2024, from https://www.stratasys.com/siteassets/materials/materials-catalog/fdm-materials/pc-iso/mds_fdm_pciso_0820a.pdf

Stratasys (2021). *FDM Nylon 12-FDM Thermoplastic Filament*. https://www.stratasys.com/siteassets/materials/materials-catalog/fdm-materials/nylon-12/mds_fdm_nylon-12_0921a.pdf?v=48d397

Stratasys (2022). *ABS-M30 FDM Thermoplastic Filament*. Retrieved May 22, 2024, from https://www.stratasys.com/contentassets/4de0cbf2401141af951112221a775f89/mds_fdm_abs-m30_0222a.pdf?v=49f8d3

Stratasys (2022). *Impact of UV Exposure on FDM Materials*; Stratasys: Eden Prairie, MI, USA.

Stratasys (2022). *PC-ABS FDM Thermoplastic Filament*. https://www.stratasys.com/contentassets/0cbbbe43e9ab4200a16c507eb99ebe7e/mds_fdm_pc-abs_0222a2.pdf?v=49c744

Stratasys (2022). *Somos ® ProtoTherm ™ 12120*. Retrieved October 16, 2024, from https://www.stratasys.com/contentassets/65f6c38632ac4bb6b4bf6e47b78f2872/sl_am_somos-prototherm-12120_leaflet_en_0123a-1.pdf?v=48f670

Stratasys (2023). *PC (Polycarbonate) FDM Thermoplastic Filament Overview*. Retrieved October 16, 2024, from https://www.stratasys.com/siteassets/materials/materials-catalog/fdm-materials/pc/mds_fdm_pc_0823a.pdf?v=4a7074

Stratasys (2023). *Somos ® PerFORM ™*. Retrieved October 16, 2024, from https://www.stratasys.com/contentassets/7c70078f60bc45b5bd0cc691ed03d3de/mds_sl_somos-perform_0123a.pdf?v=48f730

Stratasys (2024). *Kimya PC-FR*. Retrieved October 16, 2024, from https://www.stratasys.com/contentassets/f9a70939e39c4fe7b4a17fa5fce1d572/mds_fdm_kimya-pc-fr_0724a.pdf?v=4a196f

Stratasys (n.d.). *ABS-M30*. Retrieved May 22, 2024, from https://www.hubs.com/3d-printing/plastic/abs/stratasys-abs-m30/

Stratasys (n.d.). *FDM Nylon 12*. Retrieved June 25, 2024, from https://www.stratasys.com/en/materials/materials-catalog/fdm-materials/nylon-12/

Stratasys (n.d.). Somos® 9120™. Retrieved June 18, 2024, from https://www.stratasys.com/en/materials/materials-catalog/stereolithography-materials/somos-9120/

Stratasys (n.d.). *ULTEM 1010 Resin.* Retrieved May 22, 2024, from https://www.hubs.com/3d-printing/plastic/pei/stratasys-ultem-1010/

Stratasys Ltd. (2023). *Addigy P3001*. Retrieved May 28, 2024, from https://www.stratasys.com/siteassets/materials/covestro/addigy-datasheets/material.datasheet-pbf-addigy-p3001.pdf?v=4922d8

SyBridge Technologies (2020). *Know Your Materials: SLA Tough Resin*. Retrieved June 10, 2024, from https://sybridge.com/know-your-materials-sla-tough-resin/ (accessed on 10 June 2024).

SyBridge Technologies (2021a). *3 Tips for Creating Stronger Injection Molding Parts*. https://sybridge.com/tips-for-stronger-injection-molding-parts/

SyBridge Technologies (2021b). *3D Printing Clear or Translucent Parts: What You Need to Know*. https://sybridge.com/3d-printing-clear-or-translucent-parts/

SyBridge Technologies (2021c). *Ensure Injection Molding Designs are Production-Ready With This Checklist*. https://sybridge.com/injection-molding-designs-production-ready/

SyBridge Technologies (2021d). *Top 5 Impact-Resistant Plastics*. https://sybridge.com/impact-resistant-plastics/

SyBridge Technologies (2021e). *What You Need To Know About Material Compatibility For Multi-Material Injection Molding*. https://sybridge.com/material-compatibility-multi-material-injection-molding/

SyBridge Technologies (2021). *Top 5 Chemical-Resistant Plastics*. Retrieved June 12, 2024, from https://sybridge.com/top-five-chemical-resistant-plastics/

SyBridge Technologies (2022). *Achieving Food Safety Standards with Additive Manufacturing*. Retrieved June 11, 2024, from https://sybridge.com/achieving-food-safety-standards-with-additive-manufacturing/

SyBridge Technologies (2022). *Fused Deposition Modeling (FDM) Design for Manufacturing Guide*. https://sybridge.com/fdm-design-for-manufacturing-guide/

TA Instruments (2023). *Waters Corporation Evaluation of the Loss of Polymer Strength and Durability Due to Fatigue Loading and Manufacturing Artifacts*; TA Instruments: New Castle, DE, USA.

Tampi, T. (2020). *Columbia Researchers Develop Multi-Material SLS 3D Printer without Powder Bed*. Retrieved May 14, 2024, from https://3dprint.com/271117/columbia-researchers-develop-multi-material-sls-3d-printer-without-powder-bed/ (accessed on 14 May 2024).

Team Xometry (). *All About Nylon 3D Printing Filament: Materials, Properties, Definition.* Retrieved June 21, 2024 from https://www.xometry.com/resources/3d-printing/nylon-3d-printing-filament/

Team Xometry (2020). Fused Deposition Modeling (FDM) Mini-Guide. Retrieved May13, 2024, from https://www.xometry.com/resources/3d-printing/mini-guide-fdm-3d-printing/

Team Xometry (2020). *Visual Guide to SLS 3D Printing Finishes.* Retrieved May 15, 2024, from https://www.xometry.com/resources/3d-printing/visual-guide-to-sls-3d-printing-finishes/

Team Xometry (2021). What Are Heat Resistant Plastics? Retrieved June 18, 2024, from https://www.xometry.com/resources/injection-molding/heat-resistant-plastics/

Team Xometry (2022). *12 Advantages of Plastic Injection Molding*. Retrieved May 22, 2024, from https://www.xometry.com/resources/injection-molding/advantages-of-plastic-injection-molding/

Team Xometry (2022). *7 Properties of Silicone.* Retrieved June 13, 2024, from https://www.xometry.com/resources/materials/properties-of-silicone/

Team Xometry (2022). *ABS vs. PETG: Differences and Comparison*. Retrieved May 2, 2024, from https://www.xometry.com/resources/3d-printing/abs-vs-petg-3d-printing/ (accessed on 2 May 2024).

Team Xometry (2022*). All About Flex 3D Printing Filament: Materials, Properties, Definition.* Retrieved May 27, 2024, from https://www.xometry.com/resources/3d-printing/flex-3d-printing-filament/

Team Xometry (2022). *All About PET 3D Printing Filament: Materials, Properties, Definition*. Retrieved June 20, 2024, from https://www.xometry.com/resources/3d-printing/pet-3d-printing-filament/

Team Xometry (2022). *All About Selective Laser Sintering (SLS) 3D Printing*. Retrieved from https://www.xometry.com/resources/3d-printing/selective-laser-sintering-sls/ (accessed on 23 May 2024).

Team Xometry (2022). *All About Stereolithography (SLA) 3D Printing*. Retrieved February 22, 2024, from https://www.xometry.com/resources/3d-printing/stereolithography/

Team Xometry (2022). *Durometer vs. Elasticity*. Xometry. https://www.xometry.com/resources/injection-molding/durometer-vs.-elasticity/ (accessed on 3 June 2024). Archived at Wayback Machine: https://web.archive.org/web/20240627212815/https://www.xometry.com/resources/injection-molding/durometer-vs.-elasticity/ (citing a capture dated 27 June 2024).

Team Xometry (2022). Materials Used in 3D Printing: Guide to 3D Printing Materials. Retrieved July 2, 2024, from https://www.xometry.com/resources/3d-printing/3d-printing-materials/

Team Xometry (2023). *Creep (Deformation): Definition, How It Works, Importance, and Graph*. Retrieved June 17, 2024, from https://www.xometry.com/resources/3d-printing/creep-deformation/ (accessed on 17 June 2024).

Team Xometry (2023). *Creep of Polymers: Definition, Factors, Types, and Prevention.* Retrieved June 13, 2024, from https://www.xometry.com/resources/materials/creep-of-polymers/

Team Xometry (2023). *Impact Strength: Definitions, Importance, and How It Is Measured.* Retrieved June 11, 2024, from https://www.xometry.com/resources/3d-printing/impact-strength/

Team Xometry (2023). *Video: Will It Erode?—Part 1.* Retrieved June 17, 2024, from https://www.xometry.com/resources/blog/will-it-erode-pt-1/ (accessed on 17 June 2024).

Team Xometry (2023). What Is the Strongest 3D Printer Filament? Retrieved May 22, 2024, from https://www.xometry.com/resources/3d-printing/strongest-3d-printer-filament/

Team Xometry (2024) *Video: Will It Erode?—Part 2.* Retrieved June 17, 2024, from https://www.xometry.com/resources/blog/will-it-erode-pt-2/ (accessed on 17 June 2024).

Tecchio, P., Ardente, F., & Mathieux, F. (2016). *Analysis of durability, reusability and reparability - Application to washing machines and dishwashers*. Publications Office of the European Union. https://doi.org/10.2788/630157

Terzioğlu, N. (2021). Repair motivation and barriers model : Investigating user perspectives related to product repair towards a circular economy. *Journal of Cleaner Production*, *289*. https://doi.org/10.1016/j.jclepro.2020.125644

The Rodon Group Marketing Team (n.d.). *Differences in Food-Grade Plastic Injection Molding Materials*. Retrieved June 11, 2024, from https://www.rodongroup.com/blog/differences-in-food-grade-plastic-injection-molding-materials

Ultimaker (2022). *Ultimaker ABS*. Retrieved October 16, 2024, from https://support.ultimaker.com/hc/en-us/articles/360012759139-Ultimaker-ABS-TDS (accessed on 16 October 2024).

UltiMaker (2024). *How to 3D print waterproof parts*. UltiMaker. https://ultimaker.com/nl/learn/how-to-3d-print-waterproof-parts/

UltiMaker (n.d.) *Wear-Resistant Materials: A Beginner's Guide*. Retrieved June 18, 2024, from https://ultimaker.com/learn/wear-resistant-materials-a-beginners-guide/

UltiMaker (n.d.). *How to 3D Print Clear Plastic Parts*. Retrieved May 21, 2024, from https://ultimaker.com/learn/how-to-3d-print-clear-plastic-parts/

UltiMaker (n.d.). *UV-Resistant Materials: A Beginner's Guide*. Retrieved June 12, 2024, from https://ultimaker.com/learn/uv-resistant-materials-a-beginners-guide/ (accessed on 12 June 2024).

UltiMaker (n.s.). *Chemical-Resistant Materials: A Beginner's Guide*. Retrieved June 12, 2024, from https://ultimaker.com/learn/chemical-resistant-materials-a-beginners-guide/

V., C. (2023). *All You Need to Know About Polycarbonate (PC) for 3D Printing*. Retrieved June 21, 2024, from https://www.3dnatives.com/en/polycarbonate-pc-for-3d-printing-110220204/

van Oudheusden, A., Bolaños Arriola, J., Faludi, J., Flipsen, B., & Balkenende, R. (2023). 3D Printing for Repair : An Approach for Enhancing Repair. *Sustainability*, *15*(6), 51–68. https://doi.org/https://doi.org/10.3390/su15065168

van Oudheusden, A., Buijserd, A., Doubrovski, Z., & Flipsen, B. (2023). *Feasibility of On-demand Additive Manufacturing of Spare Parts*. *June*. http://resolver.tudelft.nl/uuid:71ab7e25-229a-4059-aad7-3eecf6c67ac1

VanHorne, M. (2021). 3D Printing Strength: How to 3D Print Strong Parts. Retrieved June 18, 2024, from https://all3dp.com/2/3d-printing-strength-strongest-infill/

Vicknair, A. & Renganathan, S. (2023). *Flexible 3D Printer Filament: 7 Types Compared.* Retrieved May 27, 2024, from https://all3dp.com/2/flexible-3d-printing-filament-which-should-you-chose/

Vollaro, C. (2024). *FDM vs. SLA: Comparing Filament and Resin 3D Printers*. Retrieved May 1, 2024, from https://www.protolabs.com/resources/blog/prototyping-technologies-for-3d-printing-sla-vs-fdm/

Wakefield, E. (2023). Essentium Launches Altitude Filament with Extreme Cold Resistance. Retrieved June 23, 2024, from https://www.voxelmatters.com/essentium-launches-altitude-filament-with-extreme-cold-resistance/

Wang, Z., Hu, C., Wang, W., Kong, X., & Zhang, W. (2015). A prognostics-based spare part ordering and system replacement policy for a deteriorating system subjected to a random lead time. *International Journal of Production Research*, *53*(15), 4511–4527. https://doi.org/10.1080/00207543.2014.988892

WayKen (2022). *3D Printing Surface Finish: Common Finishing Methods For 3D Printed Part*. Retrieved June 18, 2024, from https://waykenrm.com/blogs/3d-printing-surface-finish/

Xometry (2023). *Standard PEEK*. Retrieved June 18, 2024, from https://xometry.pro/wp-content/uploads/2023/08/Standard-PEEK.pdf

Xometry (2024a). *Design Guide: Fused Deposition Modeling (FDM).* https://www.xometry.com/resources/design-guides/design-guide-fused-deposition-modeling-fdm-3d-printing/

Xometry (2024b). *Design Guide: Injection Molding*. https://www.xometry.com/resources/design-guides/design-guide-injection-molding/

Xometry (2024c). *Design Guide: Selective Laser Sintering (SLS).* https://www.xometry.com/resources/design-guides/design-guide-selective-laser-sintering-sls-3d-printing/

Xometry (2024d). *Design Guide: Stereolithography*. https://www.xometry.com/resources/design-guides/design-guide-stereolithography-sla-3d-printing/

Xometry (n.d.). *Injection Molded Plastics and Elastomers*. Retrieved June 3, 2024, from https://www.xometry.com/materials/material-injection-molding/

Xometry (n.d.). *Manufacturing Standards*. Retrieved February 14, 2024, from https://www.xometry.com/manufacturing-standards/

Xometry (n.d.). *Nylon 3D Printing Service.* Retrieved June 18, 2024, from https://www.xometry.com/capabilities/3d-printing-service/3d-printing-nylon/

Xometry (n.d.). *Overmolding Service*. Retrieved May 15, 2024, from https://www.xometry.com/capabilities/injection-molding-service/overmolding/

Xometry (n.d.). *Stereolithography (SLA) 3D Printing Service*. Retrieved June 18, 2024, from https://www.xometry.com/capabilities/3d-printing-service/stereolithography-3d-printing/

Xometry Pro (2023). *10 Water-Resistant Options for Your 3D Printed Parts: Materials & Post-Processing*. Retrieved June 13, 2024, from https://xometry.pro/en-eu/articles/3d-printing-water-resistant/

Xometry Pro (2023). *Design Tips for Selective Laser Sintering (SLS) 3D Printing*. Retrieved May 13, 2024, from https://xometry.pro/en-eu/articles/3d-printing-sls-design-tips/

Xometry Pro (2023). *Food-Safe 3D Printing: Design Tips, Materials & Finishes*. Retrieved June 11, 2024, from https://xometry.pro/en-eu/articles/3d-printing-food-safe/

Xometry Pro (2023). Fused Deposition Modeling (FDM) 3D Printing Design Tips. Retrieved May 13, 2024, from https://xometry.pro/en-eu/articles/fdm-design-tips/

Xometry Pro (2023). *Injection Molding Surface Finishes: SPI and VDI*. Retrieved May 15, 2024, from https://xometry.pro/en-eu/articles/injection-molding-finishes/

Xometry Pro (2023). *Selective Laser Sintering (SLS) 3D Printing Technology Overview*. Retrieved February 22, 2024, from https://xometry.pro/en-eu/articles/3d-printing-sls-overview/

Xometry Pro (2023). *Stereolithography (SLA) 3D Printing Design Tips*. Retrieved May 1, 2024, from https://xometry.pro/en-eu/articles/3d-printing-sla-design-tips/

Xometry Pro (2023). *Stereolithography (SLA) 3D Printing Technology Overview*. Retrieved May 22, 2024, from https://xometry.pro/en-eu/articles/3d-printing-sla-overview/

Xometry Pro (2023). *Surface Finishes for 3D Printing.* Retrieved May 21, 2024, from https://xometry.pro/en-eu/articles/3d-printing-finishes/

Xometry Pro (2023). *Surface Roughness in 3D Printing*. Retrieved May 15, 2024, from https://xometry.pro/en-eu/articles/3d-printing-surface-roughness/

Xometry Pro (2024). *PA11 vs. PA12: What Are the Differences?* Retrieved June 21, 2024, from https://xometry.pro/en-eu/articles/pa11-vs-pa12/

Xometry Pro. (2023a). *Design Tips for Injection Molding*. Xometry. https://xometry.pro/en-eu/articles/injection-molding-design-tips/

Xometry Pro. (2023b). *How to Get Stronger 3D Printed Parts*. Xometry. https://xometry.pro/en-eu/articles/3d-printing-strong-parts/

Xometry Pro. (2023c). *Infographic: Design Rules for 3D Printing*. Xometry. https://xometry.pro/en-eu/articles/3d-printing-design-rules/

Xometry Pro. (2023d). *The Best Flexible Materials in 3D Printing*. Xometry. https://xometry.pro/en-eu/articles/3d-printing-flexible-materials/

Xometry Pro. (2023e). *Tolerances in 3D Printing*. Xometry. https://xometry.pro/en-eu/articles/3d-printing-tolerances/

Yang, K., & Niu, X. (2009). Research on the spare parts inventory. *2009 16th International Conference on Industrial Engineering and Engineering Management*, 1018–1021. https://doi.org/10.1109/ICIEEM.2009.5344253

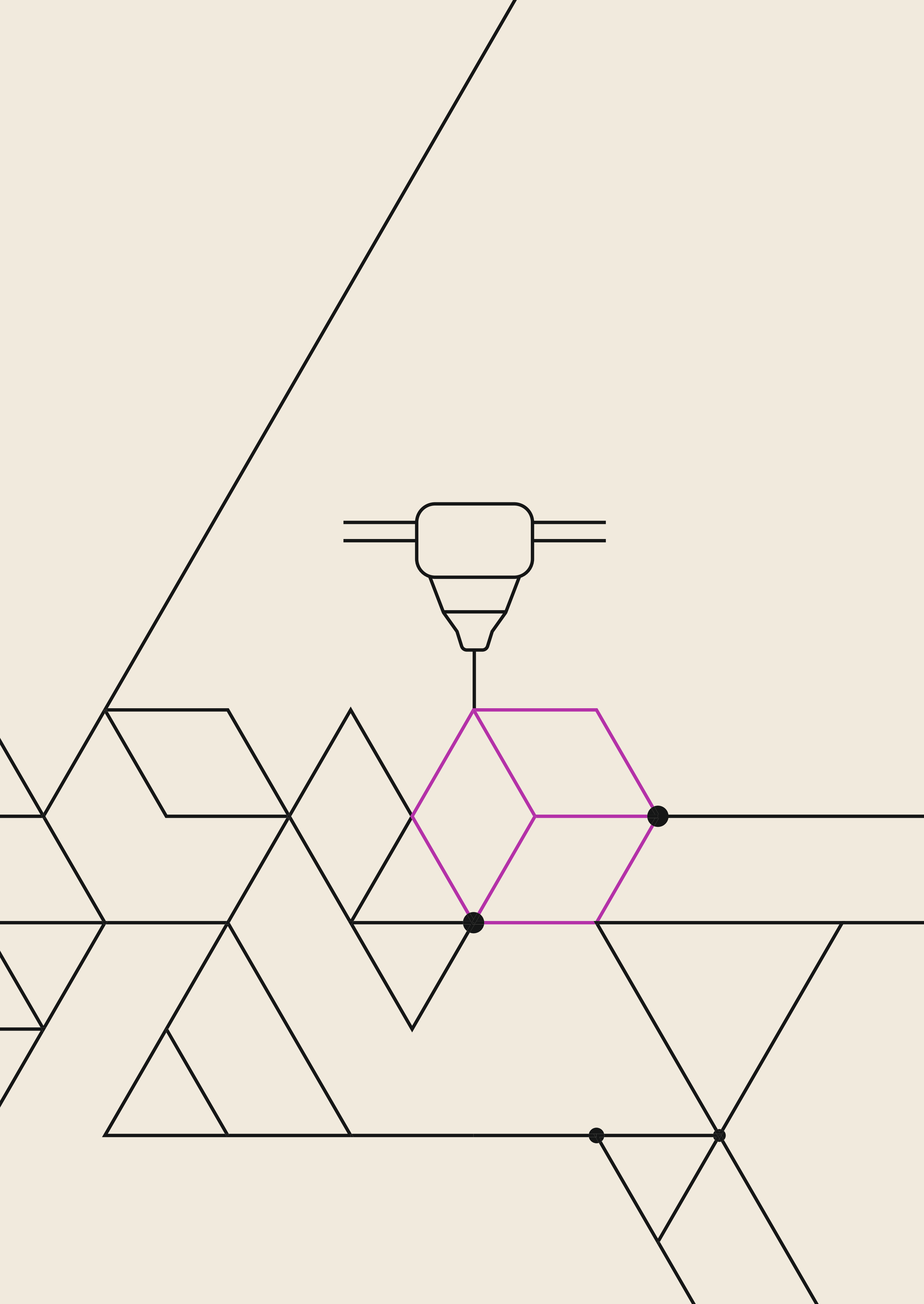
Ye, R. (2023). *Flexible Injection Moldings: LSR vs. TPE.* Retrieved May 23, 2024, from https://www.3erp.com/blog/flexible-injection-moldings-lsr-vs-tpe/

Zanoni, S., Ashourpour, M., Bacchetti, A., Zanardini, M., & Perona, M. (2019). Supply chain implications of additive manufacturing: a holistic synopsis through a collection of case studies. *International Journal of Advanced Manufacturing Technology*, *102*(9–12), 3325–3340. https://doi.org/10.1007/s00170-019-03430-w

Zetar (2022). *Common problems with transparent plastic injection molding process*. Zetar Industry Co., Ltd. https://zetarmold.com/transparent-plastic-injection-molding-process/

Zeus Industrial Products Inc. (2005). *Low Temperature Properties of Polymers*. Zeus Industrial Products, Inc. https://www.appstate.edu/~clementsjs/polymerproperties/plastics_low_temp.pdf

Zurmehlyand, K. (2019). *TPU Parts with SLS Printing*. Retrieved June 6, 2024, from https://www.fabbaloo.com/2019/10/tpu-parts-with-sls-printing



## CHAPTER 6

# Equivalent design: functionally equivalent parts through injection moulding and additive manufacturing.

Submitted as van Oudheusden, A., Faludi, J. & Balkenende, R. (2025). Equivalent design: functionally equivalent parts through injection moulding and additive manufacturing. *Cleaner Manufacturing and Technology.*

## ABSTRACT

Using additive manufacturing for the production of spare parts can increase their availability while preventing overproduction and storage costs. To facilitate the design of printed spare parts, the focus should be on achieving the same function rather than an exact replication of the original part. This study aimed to develop a method ensuring in the early stages of the design process that the injection-moulded original part and 3D-printed spare part will be functionally equivalent. We explored how this equivalent design process could look like by adapting a general design structure to consider two manufacturing methods. The resulting design approach will help designers to evaluate the impact of their design decisions on part manufacturability. This approach makes the most sense in the original part design, but it can also be used to redesign existing parts. As this design approach is relatively novel, we also propose two design tools to help designers throughout the process. Both the design process and tools were further explored in two case examples. This showed that considering the capabilities of both manufacturing methods during each design decision can ensure that the injection-moulded original part and 3D-printed spare part will be functionally equivalent.

## 6.1 INTRODUCTION

Through our fast and linear consumption, the amount of waste from consumer products is rapidly increasing (Dewberry et al., 2016). To prevent this increase in waste a move towards more circular strategies such as product repair has been suggested (Ellen MacArthur Foundation, 2013; Ghisellini et al., 2016; Terzioğlu & Wever, 2021). By facilitating repair, we can slow down the flow of resources (Bocken et al., 2016) at a lower rate of required investment than other recovery strategies (Scott & Weaver, 2014).

A significant barrier to repair is that spare parts are often unavailable once the initial production has ceased (Šajn, 2022; Zhang et al., 2021). This means consumers can typically only repair their products for a limited time, generally around two years (Hernandez & Miranda, 2020). To enable the repair of products the availability of spare parts must increase. At a European level, there are eco-design measures to extend the availability of spare parts for up to seven to ten years after the last market release (Directive 2024/1799, 2024; Šajn, 2022). Nonetheless, predicting how many spare parts will be needed is challenging and prolonged storage can be costly (Odedairo, 2021; Yang & Niu, 2009).

With additive manufacturing, spare parts can be produced long after traditional storage becomes impractical (Kim et al., 2019). Instead of maintaining a physical inventory, spare parts can be stored online and produced on demand (Pérès & Noyes, 2006; Zanoni et al., 2019). This approach will save costs and reduce waste from unused parts while supporting the repair of a product almost indefinitely (Holmström & Gutowski, 2017). Since most product parts are not designed with additive manufacturing in mind, using printed spare parts often increases the design workload (Holmström & Gutowski, 2017). The part must be redesigned to account for the characteristics of the new manufacturing process (Despeisse et al., 2017). However, there are limited opportunities to modify a design once it has been produced (Salmi & Pei, 2023). Therefore, the use of two manufacturing methods should already be considered in the initial product design (van Oudheusden et al., 2024).

Current design methods focus on designing for a single manufacturing method, or at most, how to adapt a design from one manufacturing method to another. For example, Pahl et al. (2007) proposes a systematic design approach where the manufacturing method is used to set the technological constraints. This could be useful when expanded to two manufacturing methods, but it does not consider how the differences between these methods could be overcome. To that end, Diegel et al. (2019) distinguishes three design approaches when using additive manufacturing: direct part replacement, adapt for additive manufacturing, and design for additive manufacturing. However, none of these design approaches is suited for the initial design of a product as they all focus on redesigning an existing part. Instead, a new design approach is needed that focuses on achieving the same functionality with two different manufacturing methods. Ensuring this functional equivalence in the early design stages will reduce the design workload while allowing sufficient room for design optimisation. Therefore, this paper addresses the following research question: how can a designer enable in the early stages of the design process that the injection-moulded original part and 3D-printed spare parts will be functionally equivalent?

To answer this question, we combined insights from literature and previous research to explore what a possible design process could look like. We then linked our results to earlier insights to create two tools to support the design process. Additionally, we performed two case examples to illustrate and evaluate the results.

## 6.2 METHOD

### 6.2.1 Setting up the design process structure

We set up the new design process by exploring how a standard design process could be adapted to work with two manufacturing methods. First, a general working structure was selected to represent a standard design process. The working structure we chose for this study was the design process framework by Pahl et al. (2007). This framework was constructed based on extensive research on design methodology, making it a systematic and comprehensive design approach. We defined two approaches to adapt this working structure, using the terminology by Diegel et al. (2019). This work was used as it is a fundamental work on design for additive manufacturing. The most optimal approach was selected based on what would be most beneficial in terms of manufacturing costs. To adapt the general working structure, we added, merged, and rephrased its design phases and defined possible process steps for each phase. The resulting design process was iterated and validated through the case examples.

### 6.2.2 Developing design tools

We developed two design tools to support designers in creating functionally equivalent parts. One is a function identification tool that helps designers determine the exact function of a part, regardless of the manufacturing method used. The other is a design ideation tool to give designers an example of how design challenges could be solved.

The function identification tool gives an overview of possible part functions. To create this overview, we listed the functionalities of various consumer electronics, such as a blender and a vacuum cleaner. After this list was deemed exhaustive, the part functions were matched with the design requirements in van Oudheusden et al. (2024). In that study, the design requirements were used to document and compare the manufacturing capabilities of injection moulding and additive manufacturing. By matching the functions to part requirements and reviewing the corresponding manufacturing capabilities, it becomes easier for designers to identify potential design challenges. Similar part functions were then grouped into function categories and the results were presented in a table for easy use during the design process.

The design ideation tool provides design strategies to overcome the differences between injection moulding and manufacturing. To generate these design strategies, we reviewed the design experiences of 104 students from two workshops, using the workshop setup as described in van Oudheusden et al. (2023). We listed the strategies that were used to address any design challenges and expanded on this list via further design ideation and through the design work in the case examples. The main focus here was to identify design strategies that could overcome or prevent any challenges in the design process. The resulting design strategies were then compiled into a table with examples. This overview was subsequently verified by comparing it to literature that detailed the design of printed spare parts (e.g., Chekurov & Salmi, 2017; Park, 2015; Terzioğlu, 2021; Terzioğlu et al., 2016; Terzioğlu & Wever, 2021).

### 6.2.3 Case examples

The case examples were used to illustrate and test the developed design process and tools to design functionally equivalent parts. We defined two design cases, one based on original design and the other on adaptive design. Original design goes through all phases of the design process to create a new part design, whereas adaptive design adjusts an existing part design to meet changed requirements (Pahl et al., 2007). We followed the proposed design process for both cases and documented when and how we applied the design tools. For both case examples, only the use of stereolithography (SLA), selective laser sintering (SLS), and fused deposition modelling (FDM) were considered as these printing methods are the most common and have the highest part quality (Salmi & Pei, 2023).

For the original design case, we selected the roller brush of a vacuum cleaner nozzle. This part was chosen since current designs are generally unsuitable for additive manufacturing. As such, there is potential in the equivalent design process to generate a more feasible design. Since this case focuses on original design, a variety of designs was used to determine what general requirements the part should meet.

For the adaptive design case, we selected the transparent lid of a vacuum cleaner dustbin. This part was chosen as the combination of part transparency and impact resistance is challenging to achieve with additive manufacturing. Since this case focuses on adaptive design, an existing part design was selected as a starting point for the functional analysis. This existing design was also used to create the concept design in the next phase, similar to how Pahl et al. (2007) describes adaptive design.

## 6.3 RESULTS

### 6.3.1 Design process

To set up a new design process, the design process framework of Pahl et al. (2007) was taken as starting point. This framework distinguishes the following main phases:

- "Planning and task clarification: specification of information
- Conceptual design: specification of principle solution (concept)
- Embodiment design: specification of layout (construction)
- Detail design: specification of production."

It is not always possible to draw a clear boundary between these main phases or to avoid backtracking. Instead, designers should be flexible while applying the process and adapt it to the specific design problem (Pahl et al., 2007).

When designing for both additive manufacturing and injection moulding, two design approaches can be distinguished. Following the terminology of Diegel et al. (2019), in 'Direct part replacement', one design is generated that can be manufactured with both manufacturing methods. In 'Design and adapt', two potentially different designs are created that are functionally interchangeable. By comparing these two approaches, we can determine which approach works best to design functionally equivalent parts.

For 'Direct part replacement', the design process would be similar to the standard design framework. The only difference would be that the available design space for the part would be reduced. Here, we define design space as the combination of materials and process conditions (Bastogne, 2017). The available design space is set by the boundaries of each design variable (Christensen & Bastien, 2016). For direct part replacement, the design should fit within the capabilities of two manufacturing methods instead of one, likely resulting in a smaller design space. The extent to which the design space is reduced, depends on the manufacturing methods and part requirements. The advantage of direct part replacement is that designers will be more familiar with the design process. They can design parts as usual, taking into account the reduced design space. The drawback of direct part replacement is that parts will not be fully optimised for their respective manufacturing methods. For certain part requirements, there can be relatively large gaps between the manufacturing capabilities of injection moulding and additive manufacturing (van Oudheusden et al., 2024). To accommodate these gaps, the injection moulded part would likely have to be overengineered, leading to higher cost and material use.

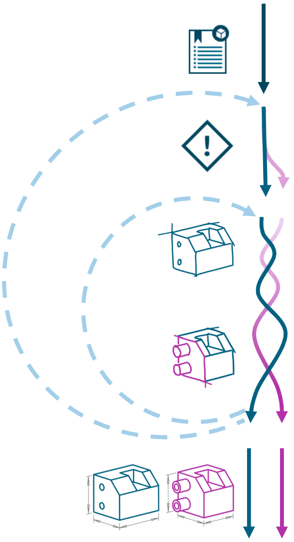
The 'Design and adapt' approach would be a more novel design process. Instead of a single design space, a designer would have to work across two design spaces. To streamline this process, the designer must prioritise one of the manufacturing methods to set the first design space. The second design space can then be determined by adapting the first design space to the secondary manufacturing method. The overlap between the design spaces depends on the specific part requirements and the gap between the capabilities of the chosen manufacturing methods. The advantage of the 'Design and adapt' approach is that there will be sufficient design space to optimise each part design to their respective manufacturing method. The drawback is that this leads to more design work and related costs. However, these might be paid back in the optimisation of the injection-moulded parts. As injection-moulded parts have large production volumes, even small savings will have a large effect.

As 'Design and Adapt' shows the best potential for optimising manufacturing costs, we chose to integrate this approach. The framework by Pahl et al. (2007) was consequently adapted, resulting in the design process in Figure 6.1. This shows an iterative design process with five phases: Design specification, Manufacturing priority, Conceptual design, Test and Adapt, and Embodiment and Detail design. Here, the Design specification phase is an adjustment of the planning and task clarification phase in Pahl et al. The planning and task clarification phase covers the entire design project, while our focus is specifically on the part design. The Manufacturing priority and Test and Adapt phases are added to the framework to reflect the 'Design and Adapt' approach. Finally, the embodiment and detail design phases are merged as the design process closely aligns with a standard design workflow at this stage. In the next subsections, these phases are explained in more detail.



#### 6.3.1.1. Design specification

The Design specification phase studies the intended functionality of the part and results in a list of design requirements. By observing the part functions in more detail, and linking these to relevant part requirements, designers can find and highlight any potential design challenges. Using these design challenges, it can be determined what additive manufacturing method would be most suitable and, in the next phase, what manufacturing method should have design priority. Below, we propose what steps this phase could include.



**Design specification** [1]
Determine the part functions and related design requirements through functional analysis.

**Manufacturing priority**
Determine which of the two manufacturing methods has priority in the design.

**Conceptual design** [2]
Ideate design solutions and choose the best solutions for the primary manufacturing method. Use this to create the primary design concept.

**Test and Adapt** [2]
Test which, if any, design choices need to be adapted to the secondary manufacturing method. Use this to create the secondary design concept.

**Embodiment and detail design**
Develop and define each part design in parallel and optimise both designs for their respective manufacturing method.

1 See Function identification tool (Table 1)
2 See Design ideation tool (Table 2)

**Figure 6.1.** The equivalent design process workflow with all design phases needed to design functionally equivalent parts when designing for two manufacturing methods, as indicated by the two differently coloured arrows. Usually, one of the manufacturing methods will be prioritised over the other.

First, part functions are determined through functional analysis, which could be through annotated sketches or the function analysis and system technique (FAST) diagram (Bytheway, 1964, as cited in Borza, 2011). Estimating how critical these functions are for the general product functionality of the product makes it easier to prioritise design decisions in later phases. Next, part functions are related to part requirements to find a suitable additive manufacturing method. For this, the analysis by van Oudheusden et al. (2024) could be used to assess whether the part requirements fall within the capabilities of a certain manufacturing method. This comparison also reveals potential design challenges by highlighting part requirements that could be difficult to meet. For example, while SLA printing can produce tough or transparent parts, achieving both simultaneously is difficult as transparent SLA parts tend to be brittle (Protolabs Network, 2024).

### Manufacturing priority

Since the equivalent design approach works with two design spaces, it is recommended to decide which manufacturing method is prioritised in the design. This choice can be made for the overall part or specified per function. The design challenges that were identified previously can be used to prioritise the appropriate manufacturing method.

Considering the manufacturability, it is likely that additive manufacturing will be prioritised for most part functions. This method is less suited to common design practice and often has limited performance compared to injection moulding (van Oudheusden et al., 2024). It will be easier to adapt a simpler design to a more versatile manufacturing method than the other way around. The prevalence of additive manufacturing for prototyping during product development may also drive designers to prioritise this manufacturing method.

Based on common practice, injection moulding could also get design priority. This manufacturing method is currently the industry standard and designers are more familiar with this method. There is also more literature and experience on adapting an injection-moulded part to additive manufacturing than vice versa, so this workflow could be easier for designers to integrate. Since mass production of the part will be done with injection moulding, optimising the design primarily for this manufacturing method will also have bigger effects on both cost and sustainability impact. It is up to the designer to choose their manufacturing priority, based on manufacturability and personal preference.

#### 6.3.1.2. Conceptual design

In the Conceptual design phase, the designer works on a design synthesis to fulfil the part functions found in the analysis phase. This involves finding suitable working principles for the identified functions and combining these into working structures (Pahl et al., 2007). The relations to other parts and the overall product architecture should also be considered, as identified in the functional analysis. Designers can then choose the optimal design solutions based on the capabilities of the prioritised manufacturing method. Combining these design choices leads to the initial synthesis of the primary design concept.



#### 6.3.1.3. Test and Adapt

The Test and Adapt phase is essentially an iteration of the concept design phase but with a stronger focus on the secondary manufacturing method. The design approach in this phase is similar to that of adaptive design. In adaptive design, the manufacturing process and form of the part might be changed, but the part function and how it fits into the product remain the same (Diegel et al., 2019). Instead, the emphasis is on geometrical, production and material issues (Pahl et al., 2007). Similarly, the Test and Adapt phase uses the function and fit of the primary design concept as a starting point for the secondary design concept. This ensures the two design concepts are sufficiently similar to facilitate functional equivalence while both designs consider their respective manufacturing capabilities.

When evaluating the primary concept design against the capabilities of the secondary manufacturing method, the main focus is to adapt any design choices that are not technically feasible. Designers can also choose to adapt choices to use unique manufacturing capabilities or to optimise the design. The adapted design choices can then be used to create the secondary design concept. This can range from minor adjustments of the primary design concept to a full second design synthesis as described in the previous phase.

The Conceptual design and Test and Adapt phases should be iterated if needed until the functional requirements of the part are met and a clear understanding of the final design structures is formed.

#### 6.3.1.4. Embodiment and detail design

Once the concept designs for both manufacturing methods have been established, there will be little interaction between them. The designer will work separately on each design to optimise it for its specific manufacturing method. In this phase, the design approach is the same as with conventional design. The embodiment design develops the design concept of the previous phase into a final product layout. This is done to where subsequent detail design, which includes design finalisation and documentation, can lead directly to production (Pahl et al., 2007).

The design can be optimised for numerous factors, including cost, production time, ease of manufacturing, weight, and material use. The exact strategies for part optimisation depend greatly on the design and manufacturing methods. It is important to note that optimising the design of one part might require adjustments to the other part as well. As such, even though the part designs are largely independent, it is still important to consider how they are interlinked.

### 6.3.2 Design tools to support the design process

As this equivalent design approach is relatively novel, designers will need additional tools to support them. These tools will help designers save time while working on parallel configurations and overcome challenging design issues. Below, we propose two design tools. The first tool is a function identification tool that can help designers to identify specific functions for their parts and link these to relevant design requirements. The second tool is a collection of design strategies that will help designers to find design solutions when ideating across two design spaces.

#### 6.3.2.1. Function identification tool

The function identification tool in Table 6.1 links part functions to design requirements that can be expected for that function. Although the part functions listed in this table are not exhaustive, the list is sufficiently comprehensive for the design of most consumer electronics. Similarly, the expected design requirements in the last column should serve as a starting point, rather than the definitive requirement list.

The function identification tool helps designers to list all the required part functions during the design specification phase. The first two columns can be used to identify part functions in the functional analysis. Subsequently, the design requirements in the final column can be used to find what manufacturing capabilities are required, for example by consulting Supplementary File S1 of van Oudheusden et al. (2024). This supplementary file details the manufacturing capabilities of injection moulding and additive manufacturing for most of the design requirements in Table 6.1 below. By reviewing the manufacturing capabilities for the expected design requirements, it becomes easier for designers to choose the preferred manufacturing method, determine manufacturing priority, and navigate the design synthesis. For example, designers can determine which additive manufacturing method is the most suitable, or choose design solutions that avoid the challenging design requirements. The overview of part functions and requirements will also help a designer to identify additional part requirements as the design progresses. Some of these functions might not come up in the initial functional analysis but as part of a design solution, which is why iteration in the design process is important.

#### 6.3.2.2. Design ideation tool

The design ideation tool in Table 6.2 is an overview of design strategies that can help designers to find design solutions when ideating across two design spaces. The main design challenge we found is that the original part design has a design space that is too limited for further redesign. As such, most of the design strategies in this table aim to extend this design space by predicting what changes are needed in the adaptive design phase. The overview in this tool is not an exhaustive list of all the design strategies that can be used to create functionally equivalent parts, but it intends to cover the major issues that a designer might encounter. The design ideation tool can be applied in the part design during the Conceptual design and Test and Adapt phases, and to gain inspiration for further design iteration.

**Table 6.1.** Function identification tool that links part functions to expected design requirements.

| Function Category | Function Specifics | Expected design requirements |
|---|---|---|
| Fitting | Connect | Accuracy, detail, shape, strength, flexibility, elasticity |
| | Position | Accuracy, detail |
| | Lock | Accuracy, detail, shape, strength, flexibility |
| | Seal | Accuracy, water/airtightness, flexibility, elasticity, multi-material |
| Structural | Strengthen | Shape, strength, impact resistance, fatigue resistance, creep resistance |
| | Support | Shape, detail, strength |
| | Resist | Strength, flexibility, elasticity, impact resistance, abrasion resistance, fatigue resistance, creep resistance, heat resistance, cold resistance, water resistance, UV resistance, chemical resistance |
| | Protect | Impact resistance, abrasion resistance, multi-material |
| Dynamic | Push | Shape, detail |
| | Rotate | Shape, detail |
| | Hinge | Detail |
| | Slide | Abrasion resistance, surface finish, detail |
| | Bend | Elasticity, flexibility |
| | Stretch | Elasticity |
| | Compress | Elasticity |
| Showing | Show, display | Transparency |
| | Inform | Detail |
| Containing | Contain, hold, store | Airtightness, accuracy |
| Transporting | Direct, channel | Shape, detail |
| | Ventilate | Detail |
| Aesthetic | Colour | Colour |
| | Contrast | Shape, detail, surface finish, multi-material, colour |
| | Pattern | Detail, surface finish |
| Tactile | Texture | Detail, surface finish, multi-material |
| | Grip | Detail, surface finish, multi-material |
| Speciality | Any keyword not mentioned above. | For example, food safety |

**Table 6.2.** Design ideation tool, presenting possible strategies to design functionally equivalent parts with additive manufacturing (AM) and injection moulding (IM).

| Design strategies | Description | Example |
|---|---|---|
| Segment | Break up the part into two or more parts to facilitate the manufacturing process or to make (partial) repair at a smaller scale possible. | The AM replacement part consists of multiple parts so different sections of the part can be printed in different materials. |
| Consolidate | Merge multiple parts into one part. | The AM part replaces multiple IM parts to avoid complex assemblies or to leverage the increased form freedom of AM. |
| Leave design space | Leave room in the primary part design to accommodate different dimensions of the secondary part design, or vice versa. | Leave space within the IM part design to increase the wall thickness in the AM part design. |
| Upgrade | Use a higher performance (material) choice in one design to make it equivalent to the other design. | Print the AM part in engineering plastic or composite to replace an IM part made from commodity plastic. |
| Overdimension | Increase the performance of the part design for the higher-performing manufacturing method so the same part design or part feature can be used for the manufacturing method with a lower performance. | The wall thickness of the IM part is thicker than needed so the AM part is strong enough with the same wall thickness. |
| Simplify | Make one part design simpler than the other to accommodate different manufacturing requirements. | The AM part has thicker sections/ walls instead of ribs and gussets for easier printing. |
| Complicate | Make one part design more complex than the other to use specific manufacturing capabilities. | The AM part has a more complex geometry that is impossible with IM, such as complex internal channels. |
| Complement | Add standardised component(s) to the part to achieve a certain performance. | Use screw thread inserts instead of printing or tapping screw thread. |
| Post-process | Use post-manufacturing treatments to increase the part performance | Add a heat-resistant coating, sanding for a smoothing surface, or drilling holes for tighter tolerances. |
| Shift focus | Instead of adjusting the part itself, target the (connection to) surrounding parts. | Change the shape of the housing to accommodate different features or connection types. |
| Change requirement | Achieve a certain part function through (a combination of) different design requirements. | Make a part flexible instead of stiff to withstand a load, or make a surface finish soft instead of hard to resist scratching. |

### 6.3.3 Case examples

This section evaluates the design process and tools by providing two case examples of what equivalent design might look like for both original and adaptive design. Here, original design creates a new part design while adaptive design adjusts an existing part design to meet changed requirements (Pahl et al., 2007). In both examples, we elaborate only on the initial design stages as only these phases are modified in the equivalent design process. The Embodiment and Detail design phase followed standard design practices for injection moulding or additive manufacturing and did not present any new insights.

#### 6.3.3.1. Original design example: vacuum cleaner roller brush

*Design specification*

Based on various roller brush designs, we identified the part functions and corresponding design requirements in Table 6.3. By comparing the manufacturing capabilities of FDM, SLS and SLA printing for these requirements, it was found that FDM would perform poorly in terms of detail and part strength, while SLA and SLS would be similarly suitable. However, SLS is generally more cost-effective and its performance can be further improved through post-processing. This makes SLS the preferred option for this part, although SLA could be used for components that require a high level of detail or surface smoothness.

**Table 6.3.** Functional analysis of the floor nozzle roller brush.

| Function Category | Function Specifics | Function criticality | Expected design requirements |
|---|---|---|---|
| Fitting | 1. Connect to the floor nozzle bottom/upper plate (reversible) | High | Accuracy, detail |
| | 2. Connect to the rotational drive axle (reversible) | High | Detail |
| Structural | 3. Resist impact, abrasion, and possible vibrations through use and accidents | High | Impact resistance, abrasion resistance |
| Dynamic | 4. Rotate the roller brush | High | Detail, abrasion resistance, surface finish |
| Specialty | 5. Collect dust and debris | High | For example through detail, abrasion resistance |
| Aesthetic | 6. Contrast with surrounding parts/ features to provide visual interest and aesthetic attractiveness (optional) | Low | For example through detail, surface finish, multi-material, colour |

*Manufacturing priority*

Comparing the expected design requirements in Table 6.3 with the manufacturing capabilities in Supplementary File S1 of van Oudheusden et al. (2024) shows that the greatest design challenges are expected to be multi-material, abrasion resistance, and impact resistance. These challenges can be addressed through correct material selection, keeping the design guidelines in mind (e.g., detail size), and using post-processing methods such as vapour smoothing. Additionally, the strategies in the design ideation tool can be used. However, considering these requirements will be more challenging for SLS than for injection moulding, it makes the most sense to have SLS as the prioritised manufacturing method.

*Conceptual design*

Before starting the conceptual design, we drew up an impression of the available design space for the roller brush, as seen in Figure 6.2. Here, the areas shaded blue indicate the contact surfaces where the roller brush connects to other parts. For this part, the part interfaces include the bottom plate and the rotational drive axle. How far these parts have already been defined, depends on the order in which the parts are designed. Additionally, a rough indication of the available design space is shaded in orange. This shows that the roller brush is limited by or (partly) determines the width and height of the floor nozzle, depending on the design sequence and choices. If the part is designed to extend outside of this design space, the surrounding parts will need further design work to accommodate this.



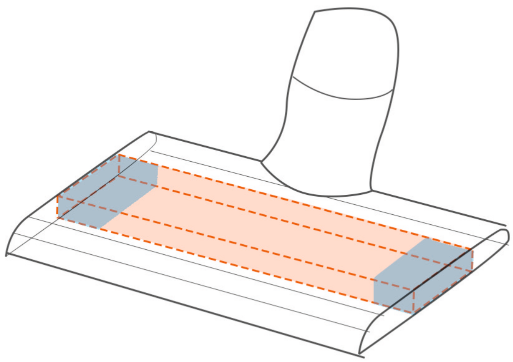


**Figure 6.2.** The location of the design space (shaded orange) and part connections (shaded blue) of the roller brush in the vacuum cleaner nozzle.

Figure 6.3 shows a sketch of the primary design concept. Below is a list of the part components indicated in Figure 6.3 and what function(s) of the functional analysis they fulfil.

1. Stopper plate: Connect to the floor nozzle bottom/upper plate (reversible)
2. Bushing: Resist abrasion from the shaft rotation
3. Shaft: Connect the inner rod to the stopper plate
4. Roller sleeve: Collect dust and debris; Contrast with surrounding parts/features (optional)
5. Inner rod: Resist impact, abrasion, and possible vibrations through use and accidents; Connect to the rotational drive axle; Rotate the roller brush

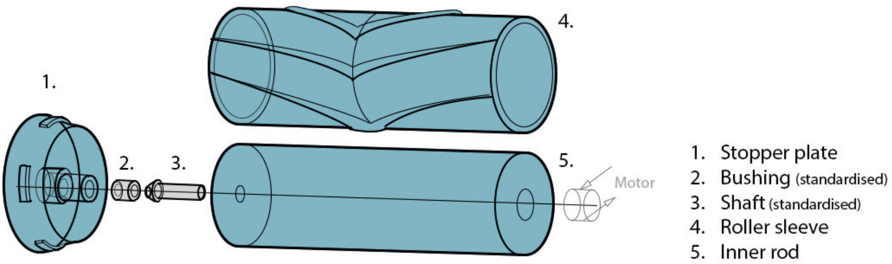



**Figure 6.3.** Exploded view of the primary design concept (additive manufacturing). Printed components are shaded blue and standardised components are light grey.

To create the primary concept design, we used the following strategies from the design ideation tool:

- Post-process: The abrasion resistance and surface finish of the stopper plate are improved through post-processing (e.g., vapour smoothing). This prevents the locking mechanism from wearing down too quickly as it is rotated in and out of place. Optionally, the roller sleeve could be dyed after printing to provide a contrasting colour.
- Upgrade: To ensure the stopper plate has the right material properties, the primary design concept uses a high-grade material such as glass-filled nylon. This is an upgrade compared to the secondary design concept, which will likely use a less advanced material. Typically, injection-moulded materials offer better abrasion resistance than printed materials, meaning a standardised non-filled material would be sufficient for this application.
- Complement: the design uses a metal shaft in the inner rod and a nylon bushing in the stopper plate. These sections of the part will encounter the most abrasion during use, so increasing the abrasion resistance through these inserts will help to improve part durability. The metal shaft can be placed through heat insertion and the nylon bushing through a press-fit.

- Change requirement: in this part design, dust and debris are collected through a ridged surface. This means that the integration of non-printable features (i.e., bristles) is no longer needed for this function. As an added benefit, the ridged roller sleeve acts as a protection barrier for the inner rod, which lowers the required impact and abrasion resistance for that component.

*Test and Adapt*

There are no design choices in the primary design concept that are not technically feasible with injection moulding. This is partly because most design decisions in the primary design also considered the use of injection moulding in the secondary design. As such, the design decisions are more intertwined than the segmentation of the design phases shows. However, some design choices could be optimised further based on certain manufacturing opportunities. For example, injection moulded parts generally have better abrasion resistance, and inserts can be integrated directly into the parts using insert moulding.

We adapted the following design choices to create the secondary design concept (Figure 6.4). The bushing is omitted as a more abrasion-resistant material (e.g., POM) can be used for the stopper plate. Additionally, the metal pin is placed into the inner rod through insert moulding instead of heat insertion, which reduces costs and manual labour during the mass production of the part. The roller sleeve remains a separate component in the secondary design, even though it could be consolidated with the inner rod through overmoulding. Keeping the sleeve separate makes it easier to replace it when it wears down instead of replacing the entire unit. This design also makes it possible to customise the ridge patterns, for example, to target different flooring types or other use scenarios.



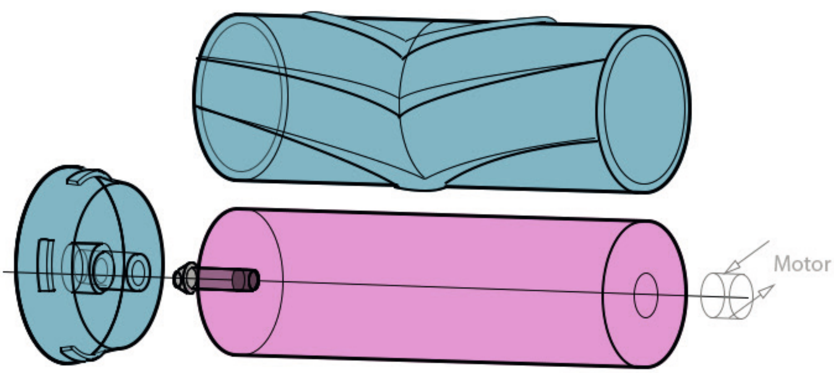



**Figure 6.4.** Exploded view of the secondary design concept (injection moulding). The adapted parts are shaded purple, the moulded but unaltered parts are blue, and the standardised components are light grey.

*Embodiment and detail design*

Figure 6.5 gives an example of what the final geometry of the part could look like, based on the previous design phases. The printed and injection-moulded designs use the same part configuration, although the latter does not include the bushing. The embodiment and detailing of both part designs are done according to the design guidelines of their respective manufacturing methods. As such, the exact embodiment of these designs will not be discussed in detail.

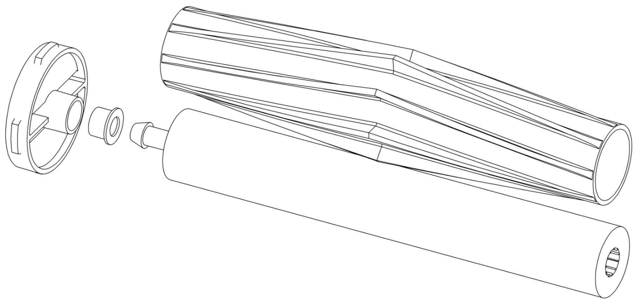


**Figure 6.5.** Embodiment design of the printed roller brush.

When optimising the parts for production, changes will likely occur between the designs of the additive-manufactured and injection-moulded parts. Key elements such as the ribs and the locking mechanism might vary, and material selection depends on the specific manufacturing method. While it is unlikely that both parts will be made from the same materials, their properties will be comparable. For example, the stopper plate could use glass-filled nylon for SLS printing and POM for injection moulding, which both prioritise abrasion resistance. The datasheets of printing materials often give an indication of what injection-moulded materials are similar to the printing material, based on the intended application. Designers can use these indications as a starting point for material selection, but part testing and manufacturer consultation are still highly recommended. Exploring unique materials, such as filled materials or specialised blends, can also be beneficial here.

### 6.3.3.2 Adaptive design: vacuum cleaner dustbin lid

*Design specification*

For the adaptive design case, we selected the transparent lid of a vacuum cleaner dustbin. Since this case focuses on adaptive design, we selected an existing part design for the functional analysis. This gave the part functions and corresponding design requirements as shown in Table 6.4. Functional analysis of the vacuum cleaner dustbin lid. When comparing additive manufacturing capabilities, FDM and SLS printing have limited to no ability to print fully transparent parts which leaves SLA printing as the best printing option.

**Table 6.4.** Functional analysis of the vacuum cleaner dustbin lid

| # | Function Category | Function Specifics | Function criticality | Expected design requirements |
|---|---|---|---|---|
| 1. | Seal | Provide an airtight (dust-tight) seal with the dustbin | High | Accuracy, airtightness |
| 2. | Display | Show the contents of the dustbin | Medium | Transparency |
| 3. | Resist | Withstand dropping on the floor | High | Impact resistance, strength |
| 4. | Connect | Clamp close on the dustbin | High | Strength, flexibility, accuracy, detail |
| 5. | Inform | Inform the user about the technology that is used in the product. | Low | Detail, surface finish, multi-material/colour |
| 6. | Aesthetic | Provide contrast colour and visual interest | Low | Detail, surface finish, multi-material/colour |

### *Manufacturing priority*

As this is an adaptive design process, we prioritise the original manufacturing method. Therefore, injection moulding is selected as manufacturing priority. This makes this adaptive design process very similar to the Adapt to AM process in Diegel et al. (2019).

### *Conceptual design*

As the original manufacturing method is prioritised, we used the original part embodiment (Figure 6.6) as the primary design concept. The part consists of two components: a transparent main body and a pink aesthetic panel connected through snap-fits.


**Figure 6.6.** The original dustbin lid as the primary design concept.

### *Test and Adapt*

When comparing the primary design concept to the manufacturing capabilities of SLA printing, the biggest design challenge is combining the transparency of the lid with the required impact resistance and strength. This is because transparent SLA resins are generally brittle (Protolabs Network, 2024), which makes it difficult to print a fully transparent part that meets all the part requirements.

To solve this issue, we used the design strategy Segment and split the main body of the primary design concept into a modified main body and transparent windowpane. Through this segmentation, the majority of the main body can be made from a stronger opaque material while the user can still look inside the dustbin through the transparent windowpane. This means that even though the secondary design concept uses a different design configuration, it is still functionally equivalent to the primary design concept. We also used Consolidate to merge the aesthetic panel and the main body of the lid by using a bright colour for the main body. Since durable SLA resins are only available in a darker colour, we switched the additive manufacturing method for the main lid body to SLS printing. The materials in this method are more suitable for post-processing strategies such as dye submersion. Additionally, the empty flat surface can be pad printed to include information on the product technology, similar to the aesthetic panel in the original part design. This shows the importance of design iteration and knowledge of additive manufacturing capabilities.

Figure 6.7 shows a sketch of the secondary design concept. Below is a list of the part components indicated in Figure 6.7 and what function(s) of the functional analysis they fulfil.

1. Transparent windowpane: Show the contents of the dustbin
2. Main lid body: Withstand dropping on the floor; Clamp close on dustbin; Inform the user about the technology used in the product; Provide contrast colour and visual interest.
3. Seal: Provide an airtight (dust-tight) seal with the dustbin

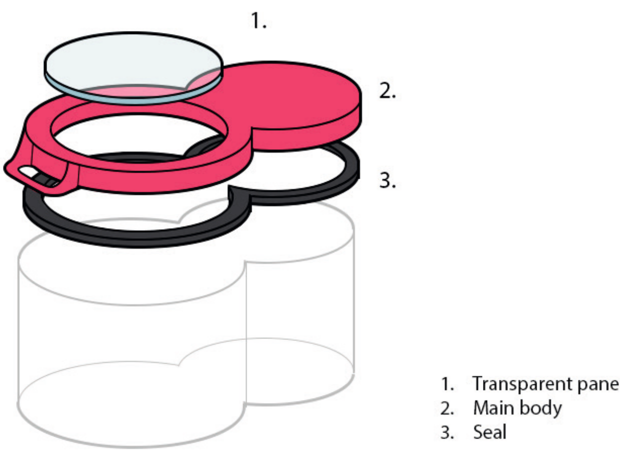



**Figure 6.7.** The secondary design concept for the dustbin lid.

*Embodiment and detail design*

Figure 6.8 gives an example of what the final geometry of the parts could look like, based on the previous design phases. Both designs feature a main body that clips onto the dustbin with a round insert at the top of the lid. In the injection-moulded part, this insert adds aesthetic contrast, while in the printed version it provides transparency. The embodiment and detailing of both part designs are done according to the design guidelines of their respective manufacturing methods. As such, the exact embodiment of these designs will not be discussed in detail. However, Figure 6.8 illustrates more clearly than the previous case example how the design of the parts might vary while still being functionally equivalent.


**Figure 6.8.** The part designs for injection moulding (left) and additive manufacturing (right) are functionally equivalent but not identical. The clear and opaque sides are switched because transparent additive manufacturing materials lack the necessary strength and impact resistance for the lid's main body. Transparent injection-moulding materials do, which is why the main body can be made transparent for better visibility inside the dustbin.



## 6.4 DISCUSSION

In this paper, we presented a new design approach to enable in the early stages of the design process that an injection-moulded original part and a 3D-printed spare part will be functionally equivalent. This design approach helps designers to properly consider the impact of their design decisions on part manufacturability. Determining the design priority for a particular manufacturing technology in the early design stages streamlines the process and facilitates adapting the design from one manufacturing method to another. This is also addressed in the Test and Adapt phase, where the concept design for the prioritised manufacturing method is tested for its compatibility with the second manufacturing method. This ensures that both designs will be functionally equivalent, even after further optimisation in a later phase.

Although the equivalent design method was constructed based on the design studies of Diegel et al. (2019) and Pahl et al. (2007), there are some important differences. For example, although the equivalent design method resembles the Adapt for AM design method as specified by Diegel et al. (2019), the latter starts the adaptive design from the detail design of an existing part, rather than from its original function. As such, the original design is unlikely to be changed, which limits the possibilities for adjusting or optimising the available design space for a second manufacturing method. Additionally, Adapt for AM always assumes that the manufacturing method of the original part (i.e., injection moulding) will have priority, whereas with equivalent design, this could also be the other way around. Compared to the design method by Pahl et al. (2007), the equivalent design process gives designers more guidance to work across two different design spaces by considering how the design choices for one manufacturing method affect the design for another manufacturing method. This gives more opportunity to optimise each design individually for its manufacturing method, rather than designing parts within the technical constraints of both manufacturing methods.

In our case examples, we explored how equivalent design could be used for both the original design of new products and the adaptive design of existing products. The original design case example started from the initial functionality of the part and used design solutions that worked for both manufacturing methods. As a result, both designs were more streamlined with no obvious indication that the part was designed with two manufacturing methods in mind. This is because the conceptual design for the prioritised manufacturing method considered the manufacturing capabilities of the second manufacturing method, which meant that no technical limitations had to be overcome in the secondary design. For the adaptive design case example, the design of an existing part was used to create the conceptual design. This made it more obvious in the secondary design that changes were added after the original design had already been established. This is because adaptive design has a reduced design space and works with a determined set of design decisions. This limits a designer in their ability to optimise design decisions or to think of novel working structures, much like the Adapt for AM approach as described by Diegel et al. (2019). To fully use the potential of equivalent design, it makes the most sense to use it in an original design process. This does not mean that the adaptive design of existing products should be avoided. Rather, more careful and creative consideration of the design limitations is needed in that case.

The case examples in this paper show that only small changes are needed in a design to have a big effect on part printability. This means that equivalent design is not the same as designing in parallel configurations. Instead, it is a way of design where a design decision is considered twice for two different manufacturing methods. As seen in the case example of the roller brush, choosing a ridged pattern instead of overmoulded bristles has a large effect on part printability. Similarly, the case examples show how the design strategies of the design ideation tool (Table 6.2) can be used to overcome or avoid challenging part requirements. For example, using a nylon bushing in the roller brush reduced the abrasion resistance requirements, whereas separating the dustbin lid into a body and windowpane made it possible to avoid the challenge of combining transparency and strength. Outside the case examples, the design strategies reflect plenty of other minor changes that could have big effects. For example, internal components could be slightly rearranged to leave design space for an increased wall thickness, or the size or shape of a part or feature could be changed to fit the capabilities of both requirements.

True functional equivalence is achieved through multi-stage design decisions, rather than a fully new design approach or additional design steps. The development of the primary and secondary design concepts are presented separately in the case examples, but in practice, the design decisions and concept developments were highly intertwined. For example, the primary design concept of the roller brush considered whether the components were suitable for additive manufacturing, but also whether the design would make sense for mass production. As such, the primary design concept avoided working structures and design solutions with considerable material use. If the secondary manufacturing method is kept in mind while making design decisions for the primary manufacturing method, it will be easier to adapt and optimise these design choices in later phases. This means a designer will already have a good idea of what the secondary design concept will look like while the primary design concept is still being developed. Also, evaluating the design decisions as they are made means that design iteration will be much faster as there is more room to change the connected design decisions. The design method and tools presented in this paper can facilitate this form of integrated decision-making by structuring the process and providing the designer with new insights on how to design for two manufacturing methods.



Although the equivalent design method simplifies the production of printed spare parts, it does not automatically result in a more circular product. With equivalent design, designers can more easily enable the use of printed spare parts in the initial product design. This increases the availability of spare parts, making repairs more accessible. As a result, the product lifetime is increased, which should reduce the environmental impact of the product (van Nes & Cramer, 2006). However, the availability of spare parts is not the only barrier to repair. A product not designed for repair may still not be repaired, even if spare parts are available. Therefore, equivalent design should be combined with circular design methods such as design for repair. This means products should be easy to disassemble and parts with a higher failure rate should be easy to access (Huang et al., 2016). When combined with equivalent design, designers also need to avoid non-printable components. For instance, the first case example suggested insert moulding and overmoulding for the injection-moulded design. While we included these design strategies to highlight the potential of equivalent design, these are not favourable decisions regarding repairability and recyclability. This might be an advantage of prioritising additive manufacturing in the design process, as design for additive manufacturing generally avoids these less favourable strategies.

### Limitations and recommendations

We did not fully explore the design process and its potential as the case examples did not include a detailed exploration of the Embodiment and Detail design phase. While this phase should be identical to existing design practices for additive manufacturing and injection moulding, there might be occasions where designers would loop back from these design phases for iteration. Additionally, the exploration included only one short iteration, which means the design does not fully reflect the potential of equivalent design. More illustrative and insightful design decisions could be explored. The same goes for the design tools. These were constructed based on the work of various designers, but the tools have not been validated beyond the presented case studies.

Future research could give further trials of the design process to advance it. This could include additional part categories and parts with different design requirements to see if these give new insights. Additionally, this study has focused on more of a part level than a product level, so considering the process using a more holistic perspective might be worthwhile. This could include further consideration of the connections to other parts and the available design space, as mentioned in the first case example.

## 6.5 CONCLUSION

This study shows that, when using additive manufacturing to produce spare parts, they can be functionally equivalent to injection moulded parts by considering the capabilities of both manufacturing methods in each design decision. The design approach presented in this paper supports designers in this process. The approach’s determination of design priority at the start helps to streamline the process and facilitate the adaptation. Most times, only small design changes will be needed to have a large impact on the suitability of a design for additive manufacturing. This means that the equivalent design process will help designers more when used in the original design of products, compared to the redesign of existing products. This prevents designers from being too limited by the existing structures and decisions of the original design. Instead, a designer can favour the design choices that are suitable for both manufacturing methods. To ensure that printed spare parts also increase the circularity of the product, equivalent design should be combined with circular design approaches such as design for repair. It is only through the careful design of a product and its parts that we can prevent waste and move towards a more circular economy.

## 6.6 REFERENCES

Bastogne, T. (2017). Quality-by-design of nanopharmaceuticals – a state of the art. In *Nanomedicine: Nanotechnology, Biology, and Medicine* (Vol. 13, Issue 7, pp. 2151–2157). Elsevier Inc. https://doi.org/10.1016/j.nano.2017.05.014

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

Borza, J. (2011). *FAST Diagrams: The Foundation for Creating Effective Function Models General Dynamics Land Systems*.

Chekurov, S., & Salmi, M. (2017). Additive Manufacturing in Offsite Repair of Consumer Electronics. *Physics Procedia*, *89*, 23–30. https://doi.org/10.1016/j.phpro.2017.08.009

Christensen, Jesper., & Bastien, Christophe. (2016). *Nonlinear optimisation of vehicle safety structures : modeling of structures subjected to large deformations*. Butterworth-Heinemann.

Despeisse, M., Baumers, M., Brown, P., Charnley, F., Ford, S. J., Garmulewicz, A., Knowles, S., Minshall, T. H. W., Mortara, L., Reed-Tsochas, F. P., & Rowley, J. (2017). Unlocking value for a circular economy through 3D printing: A research agenda. *Technological Forecasting and Social Change*, *115*, 75–84. https://doi.org/10.1016/j.techfore.2016.09.021

Dewberry, E. L., Saca, L., Moreno, M., Sheldrick, L., Sinclair, M., Makatsoris, C., & Charter, M. (2016). A landscape of repair. *Proceedings of the Sustainable Innovation 2016. Circular Economy Innovation and Design.*, 76–85. https://cfsd.org.uk/events/sustainable-innovation-2016/

Diegel, O., Nordin, A., & Motte, D. (2019). *Additive Manufacturing Technologies BT - A Practical Guide to Design for Additive Manufacturing*. Springer Nature Singapore Pte Ltd. https://doi.org/10.1007/978-981-13-8281-9_2

Ellen MacArthur Foundation. (2013). *TOWARDS THE CIRCULAR ECONOMY Economic and business rationale for an accelerated transition*.

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Hernandez, R. J., & Miranda, C. (2020). *Empowering Sustainable Consumption by Giving Back to Consumers the 'Right to Repair.'* 1–15.

Holmström, J., & Gutowski, T. (2017). Additive Manufacturing in Operations and Supply Chain Management: No Sustainability Benefit or Virtuous Knock-On Opportunities? *Journal of Industrial Ecology*, *21*, S21–S24. https://doi.org/10.1111/jiec.12580

Huang, J., Esmaeilian, B., & Behdad, S. (2016). DESIGN FOR EASE-OF-REPAIR: INSIGHTS FROM CONSUMERS' REPAIR EXPERIENCES. *Proceedings of the ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. http://proceedings.asmedigitalcollection.asme.org/pdfaccess.ashx?url=/data/conferences/asmep/90691/

Kim, H., Cha, M., Kim, B. C., Lee, I., & Mun, D. (2019). Maintenance Framework for Repairing Partially Damaged Parts Using 3D Printing. *International Journal of Precision Engineering and Manufacturing*, *20*(8), 1451–1464. https://doi.org/10.1007/s12541-019-00132-x

Odedairo, B. O. (2021). Managing Spare Parts Inventory by Incorporating Holding Costs and Storage Constraints. *Journal of Engineering, Project, and Production Management*, *11*(2), 139–144. https://doi.org/10.2478/jeppm-2021-0014

Directive 2024/1799. (2024). *Directive (EU) 2024/1799 of the European Parliament and of the Council of 13 June 2024 on common rules promoting the repair of goods and amending Regulation (EU) 2017/2394 and Directives (EU) 2019/771 and (EU) 2020/1828Text with EEA relevance.* http://data.europa.eu/eli/dir/2024/1799/oj

Pahl, G., Beitz, W., Feldhusen, J., & Grote, K.-H. (2007). *Engineering Design A Systematic Approach* (K. Wallace & L. Blessing, Eds.; 3rd ed.). Springer-Verlag.

Park, M. (2015). Print to Repair: Opportunities and Constraints of 3D printing replacement parts. *PLATE: Product Lifetimes And The Environment*, 270–276. https://www.plateconference.org/print-repair-opportunities-constraints-3d-printing-replacement-parts/

Pérès, F., & Noyes, D. (2006). Envisioning e-logistics developments: Making spare parts in situ and on demand. State of the art and guidelines for future developments. *Computers in Industry*, *57*(6), 490–503. https://doi.org/10.1016/j.compind.2006.02.010

Protolabs Network. (2024). *What's the right resin for SLA? 3D printing materials compared*. 3D HUBS B.V. https://www.hubs.com/knowledge-base/sla-3d-printing-materials-compared/

Šajn, N. (2022). *Right to Repair.* European Parliamentary Research Service. https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/698869/EPRS_BRI(2022)698869_EN.pdf

Salmi, M., & Pei, E. (2023). Additive manufacturing processes and materials for spare parts. *Journal of Mechanical Science and Technology*, *37*(11), 5979–5990. https://doi.org/10.1007/s12206-023-1034-0

Scott, K. A., & Weaver, S. T. (2014). To Repair or Not to Repair: What is the Motivation? *Journal of Research for Consumers*, *January 2014*, 1–31.

Terzioğlu, N. (2021). Repair motivation and barriers model : Investigating user perspectives related to product repair towards a circular economy. *Journal of Cleaner Production*, *289*. https://doi.org/10.1016/j.jclepro.2020.125644

Terzioğlu, N., Brass, C., & Lockton, D. (2016). 3D Printing for Repair : A Paradigm Shift in Fixing Our Relationships with Things. *Sustainable Innovation*, *November*(21st international conference), 274–281.

Terzioğlu, N., & Wever, R. (2021). Integrating repair into product design education: Insights on repair, design and sustainability. *Sustainability (Switzerland)*, *13*(18). https://doi.org/10.3390/su131810067

van Nes, N., & Cramer, J. (2006). Product lifetime optimisation: a challenging strategy towards more sustainable consumption patterns. *Journal of Cleaner Production*, *14*(15–16), 1307–1318. https://doi.org/10.1016/j.jclepro.2005.04.006

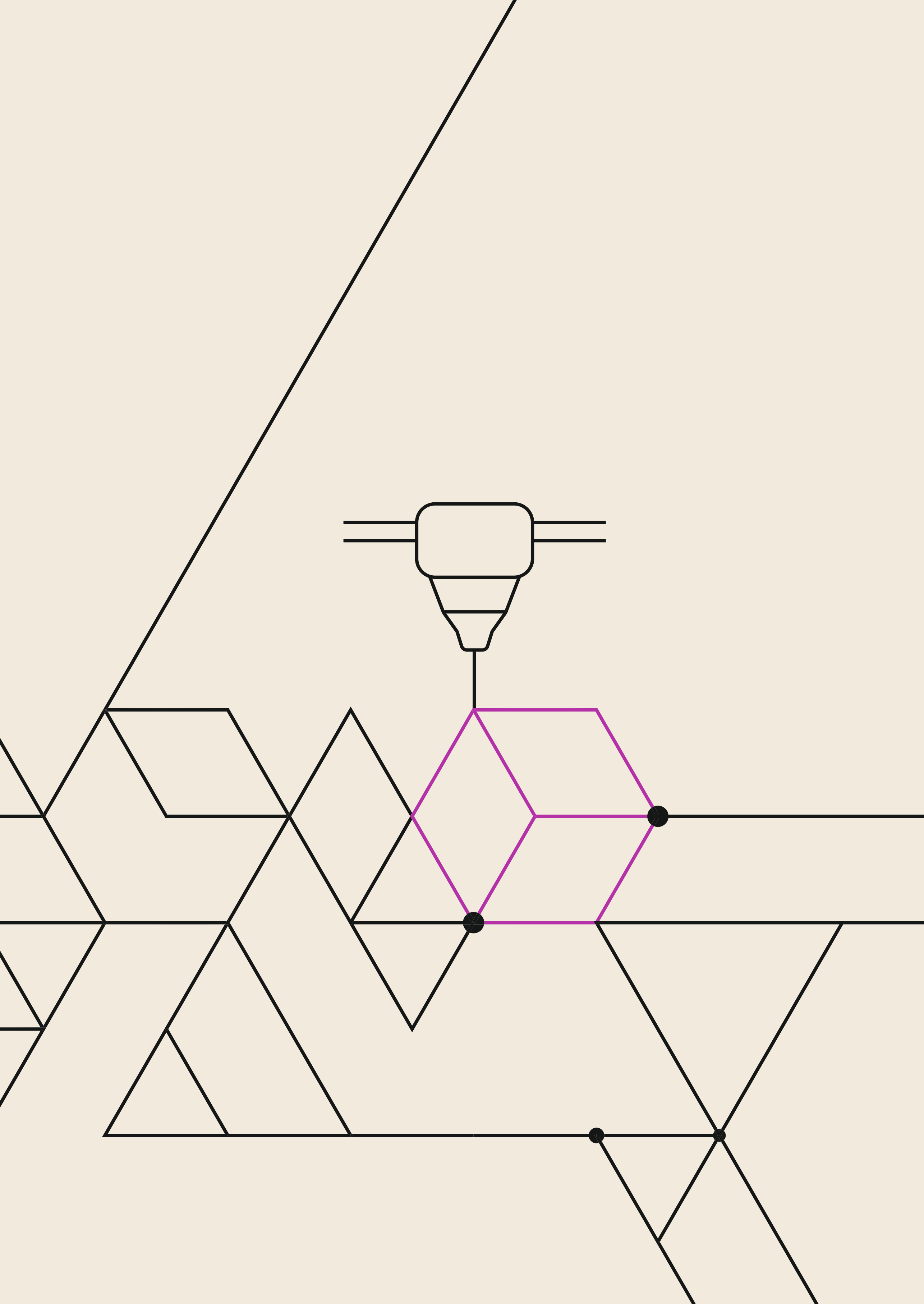
van Oudheusden, A., Bolaños Arriola, J., Faludi, J., Flipsen, B., & Balkenende, R. (2023). 3D Printing for Repair : An Approach for Enhancing Repair. *Sustainability*, *15*(6), 51–68. https://doi.org/https://doi.org/10.3390/su15065168

van Oudheusden, A., Faludi, J., & Balkenende, R. (2024). Facilitating the Production of 3D-Printed Spare Parts in the Design of Plastic Parts: A Design Requirement Review. *Sustainability (Switzerland)*, *16*(21). https://doi.org/10.3390/su16219203

Yang, K., & Niu, X. (2009). Research on the spare parts inventory. *2009 16th International Conference on Industrial Engineering and Engineering Management*, 1018–1021. https://doi.org/10.1109/ICIEEM.2009.5344253

Zanoni, S., Ashourpour, M., Bacchetti, A., Zanardini, M., & Perona, M. (2019). Supply chain implications of additive manufacturing: a holistic synopsis through a collection of case studies. *International Journal of Advanced Manufacturing Technology*, *102*(9–12), 3325–3340. https://doi.org/10.1007/s00170-019-03430-w

Zhang, S., Huang, K., & Yuan, Y. (2021). Spare parts inventory management: A literature review. *Sustainability (Switzerland)*, *13*(5), 1–23. https://doi.org/10.3390/su13052460



CHAPTER 7

# Discussion and Conclusion

## 7.1 SUMMARY OF RESEARCH FINDINGS

Printed spare parts are designed to increase the repairability of products, which fits the principles of the circular economy. One of the core principles of the circular economy is that the value of products should be preserved by extending product lifetimes (Bocken et al., 2016). The repair of products is one of the most effective ways to achieve this goal (Laitala et al., 2020). Additionally, additive manufacturing is a promising production method in the circular economy when balancing its benefits and limitations (Tavares et al., 2023). This highlights the importance of combining the design of printed spare parts with circular design methods such as design for repair. The flexibility of digital files can also make it easier to upgrade parts or enable value-added repair (Ford & Despeisse, 2016; Sauerwein et al., 2019).

The goal of this study was to answer the following main research questions:

**RQ1.** What design aspects of plastic spare parts in consumer products determine whether or not they are suitable for additive manufacturing?

**RQ2.** How should we design plastic parts to make them more suitable for additive manufacturing of spare parts?

To answer these research questions, we also included two design perspectives: consumer design and manufacturer design. Chapter 1 explains that for consumer design, the design of a printed spare part is made by consumers as part of the repair process, whereas for manufacturer design, this design is created during the initial design of the product. RQ1 was answered from a consumer perspective in Chapters 2 and 3, and a manufacturer perspective in Chapters 4 and 5. RQ2 was answered from a consumer perspective in Chapter 3 and a manufacturer perspective in Chapters 5 and 6. Below, Table 7.1 (replicated from Table 1.1 in Chapter 1) shows how the sub-questions of this dissertation relate to the main research questions and design perspectives.

**Table 7.1.** The sub-questions of each chapter in relation to the main research questions and design perspectives. Replicated from Table 1.1 in Chapter 1.

<table>
<tr><th></th><th>Consumer perspective</th><th>Manufacturer perspective</th></tr>
<tr><td rowspan="2">RQ1. Suitable aspects for additive manufacturing</td><td colspan="2">RQ1.1. How can we evaluate the printability of product parts based on part requirements? (Chapter 4)</td></tr>
<tr><td>RQ1.2. What repairs within repair communities can be met through 3D-printing spare parts? (Chapter 2)</td><td>RQ1.3. Which design requirements drive the design for both injection moulding and additive manufacturing? (Chapter 5)</td></tr>
<tr><td rowspan="2">RQ2. Designing printed spare parts</td><td>RQ2.1. How can the 3DPfR process that leads to a successful repair be described? (Chapter 3)</td><td>RQ2.3. How can these design requirements be used to facilitate the design of 3D-printed spare parts? (Chapter 5)</td></tr>
<tr><td>RQ2.2. What is the influence of previous experience, process implementation, and part complexity on the overall success of the 3DPfR process? (Chapter 3)</td><td>RQ2.4. How can a designer enable in the early stages of the design process that the injection-moulded original part and 3D-printed spare parts will be functionally equivalent? (Chapter 6)</td></tr>
</table>

**Chapter 2** studied what repairs in repair communities can be met through 3D-printing spare parts (**RQ1.2**). Through analysing the Open Repair Database, we estimated that 8% - 29% of non-repaired items in repair cafés might benefit from 3D-printed spare parts based on their repair and product types. Suitable repairs were mainly those with mechanical part failures, whereas small kitchen items was one of the most promising product categories for 3D-printed spare parts. However, this study found that more insight was needed into what design aspects determine whether a part is likely to succeed in 3D printing.



In **Chapter 3**, the insights from Chapter 2 were used to establish a framework on how to integrate printed spare parts into consumer self-repair (**RQ2.1**). Through literature review and experimental study, validated through a practical analysis of 45 cases, we set up the 3D-printing for Repair (3DPfR) process (Figure 7.1). This design process was developed for self-repair by consumers and repair communities to help them create a printed replacement for the broken or missing product part in their repair. The 3DPfR process consists of four phases: analyse, (re)design, manufacture, and test. To ensure this design approach is successful, it is essential to guide consumers in making the right design decisions during the design phase. As a printed part often cannot be a direct copy of the original part, the part design will likely need multiple iterations to obtain the right part performance and fit. The number of iterations and required design work could limit the appeal of this approach for consumers and result in a relatively high environmental impact.

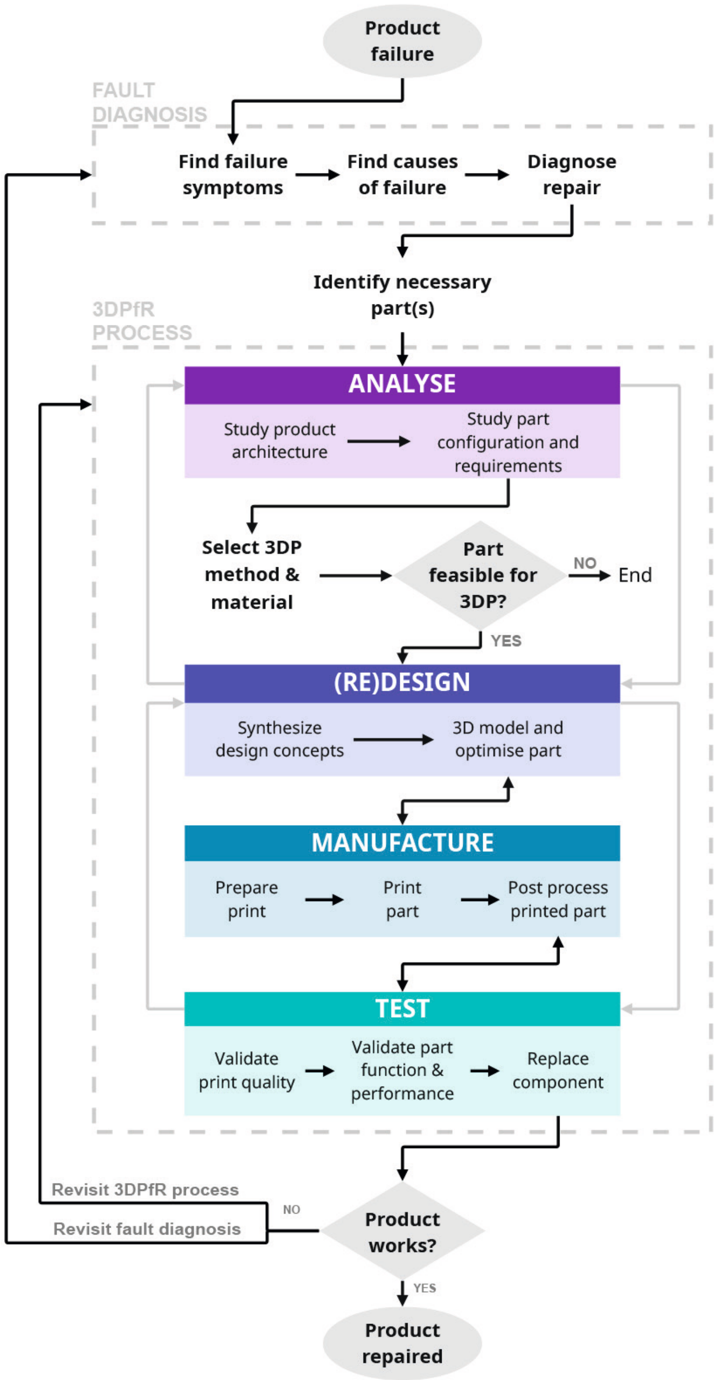



**Figure 7.1.** 3DPfR framework. Replicated from Figure 3.12 in Chapter 3.

Chapter 3 also sought to find what process factors are relevant for a successful repair (**RQ2.2**). By analysing the repair results from 45 students, we found that execution of the process steps was the most important predictor for a successful repair. This shows that it is especially important to guide users in making the right design decisions during the redesign of their part. This study also showed it is difficult to predict which parts are suitable for additive manufacturing. Most likely, the suitability of a part depends on the strictness of the part requirements, rather than their type. A part that needs high performance for a relatively easy requirement may be difficult to print, while a part with low performance for a challenging requirement might still be feasible. Ultimately, it depends on whether the required part properties are within the capabilities of additive manufacturing. The studies in Chapters 4 and 5 support this assumption: specifying the required performance for each part requirement makes it easier to determine what manufacturing capabilities are needed and whether this is feasible with additive manufacturing.

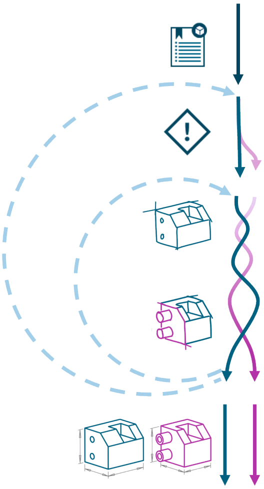
**Chapter 4** used the framework and findings from Chapter 3 to explore how we can evaluate the printability of product parts based on part requirements (**RQ1.1**). We constructed a list of part requirements and used these in a theoretical assessment, validated through a practical case study. Here, we defined eight limiting criteria by specifying the expected performance levels that would restrict part printability. These limiting criteria were used to calculate a part printability rating, starting with a score of nine and subtracting one point for each applicable limiting criterion. A low printability score indicates that a part will be more difficult to print and careful consideration is needed of the printing method, printing material, and printer settings. However, we observed that several parts were sensitive to printability issues despite a high printability score, which led to additional assessment criteria. Based on the results, we conclude that printed spare parts can be affordable, but that only a small selection of parts is currently suitable for additive manufacturing. Overall product complexity and part requirements such as fine details and accurate fit can make it difficult to reproduce parts without considerable redesign efforts.



**Chapter 5** analysed which design requirements drive the design for both injection moulding and additive manufacturing (**RQ1.3**). Both these methods are needed from a manufacturing perspective to ensure that the original part and printed spare part can be manufactured and interchanged successfully. Based on the design requirements from Chapters 3 and 4, along with insights from further literature review, we listed a total of 20 requirements categorized into five groups. While there are potentially an infinite number of design requirements, the illustrative case demonstrated that most requirements are covered by a limited number of requirements.

Chapter 5 also studied how these design requirements can be used to facilitate the design of 3D-printed spare parts (**RQ2.3**). By comparing the capabilities of injection moulding and additive manufacturing on an industrial level, we gained further insight into potential design challenges for manufacturers. While specific design considerations are needed for many requirements, most challenges could be overcome through careful design. Only a few requirements, like multi-material and food safety, will always be challenging to achieve with additive manufacturing. Additionally, design challenges can also arise from challenging combinations of design requirements. When designing printed spare parts, designers should consider the trade-offs and synergies between design requirements and manufacturing capabilities. This represents a broader design challenge where designers must be fluent in both injection moulding and additive manufacturing design.

**Chapter 6** uses the insights of the previous chapters to construct a new design approach for manufacturers to enable the use of printed spare parts in the original design of the part (**RQ4.2**). We developed the equivalent design process (see Figure 7.2) by adapting an existing design framework for use with both manufacturing methods, aiming to design parts with the same functionality but different designs. In this process, each design decision is considered twice to ensure functional equivalence. By determining the design priority at the beginning, the design process becomes more efficient. Generally, only small adjustments are needed to ensure that a part design can be made suitable for both manufacturing methods. This means that designing plastic parts for additive manufacturing is more beneficial during the initial product design, rather than when redesigning existing products.




1 See Function identification tool (Table 1)
2 See Design ideation tool (Table 2)

**Figure 7.2.** The equivalent design process workflow with all design phases needed to design functionally equivalent parts when designing for two manufacturing methods, as indicated by the two differently coloured arrows. Usually, one of the manufacturing methods will be prioritised over the other. Replicated from Figure 6.1 in Chapter 6.

## 7.2 CORE PRINCIPLES OF 3D-PRINTED SPARE PARTS



Combining the results of the research questions and design perspectives, we derived five core principles of 3D-printed spare parts. These principles reflect the most important considerations when designing printed spare parts, regardless of which design approach is used. The equivalent design process, when used by manufacturers, will be most effective in applying these principles. However, principles 1, 2 and 3 can also be applied in 3D printing for Repair by consumers.

### 1. Form follows fabrication

*Manufacturer and consumer design – Chapters 3, 5, and 6*

The design of a printed spare part should focus on its intended function, rather than replicating its material or shape. This is especially important when redesigning or reverse-engineering existing parts. As shown by the comparison of manufacturing capabilities in Chapter 5 (Table 5.4), additive manufacturing is not simply a drop-in replacement for injection moulding. Instead, most printed parts and materials will perform differently from the original parts and materials they replace. To facilitate the design of printed spare parts, designers should concentrate on creating parts that are functionally equivalent, rather than identical. This is the main focus of the equivalent design process outlined in Chapter 6 (Figure 6.1). Prioritising functional equivalence will reduce the design workload while providing considerable flexibility for design optimisation based on the respective manufacturing capabilities. The 3DPfR process discussed in Chapter 3 (Figure 3.12) is less effective in applying this principle than Chapter 6's approach for manufacturers, but it can be considered during both the analysis and redesign phases to streamline the design process.

**2. Small changes, big results**

*Manufacturer and consumer design – Chapters 4, 5, and 6*

While most part designs are currently unsuitable for additive manufacturing, only small adjustments are generally required to ensure that a part design is suitable for both injection moulding and additive manufacturing. When evaluating the printability of a vacuum cleaner in Chapter 4, nearly all parts encountered one or more criteria that limited part printability, but most parts were still printable. Similarly, the design challenges presented in the case examples in Chapter 5 could generally be addressed through careful design. Chapter 5's printability evaluation tool (as demonstrated in Tables 5.5 and 5.6) should help designers to identify any challenges in the design. To overcome these challenges, designers can use the design ideation tool in Chapter 6 (Table 6.2) to develop solutions that are suitable for both injection moulding and additive manufacturing.

**3. Everything is connected**

*Manufacturer and consumer design – Chapters 5 and 6*

Rather than a single complex requirement, it is the combination of part requirements that determines part suitability the most. A careful balance between design, material, and manufacturing is needed to realise printed spare parts. While Chapter 5 (Table 5.4) lists the material properties and manufacturing capabilities for all design requirements separately, these properties are often interconnected and relevant to more than one requirement. Therefore, the design requirements should be considered in the context of their overall functionality. The function identification tool in Chapter 6 (Table 6.1) can be used to facilitate this process and provide more insight into how the design requirements are interconnected throughout the part.

**4. Be an early bird**

*Manufacturer design – Chapters 3, 5, and 6*

It is easier to enable 3D-printed spare parts early in the design, as both the part designs for injection moulding and additive manufacturing can still be modified. This flexibility allows designers to prioritise design solutions that work for both manufacturing methods, as shown in the equivalent design process in Chapter 6 (Figure 6.1). If printed spare parts are introduced later in the product lifecycle, as seen in the 3DPfR process in Chapter 3 (Figure 3.12), the design process becomes less flexible. Since the designer needs to consider an already-existing product, they are limited in their ability to optimise design decisions or to explore novel working structures. While printed spare parts can still be used for existing products, more careful consideration of the design limitations is needed in that case.

**5. Focus on parts, not assemblies**

*Manufacturer design – Chapters 4, 5, and 6*

The current design of products generally makes it difficult to disassemble them, with most parts being integrated into larger subassemblies. During the disassembly of a vacuum cleaner in Chapter 4, we found that 10 out of 23 subassemblies could not be fully taken apart. The complexity of these subassemblies, along with multi-material and non-printable part features, makes it impossible to reproduce them with additive manufacturing, as shown in Chapter 5. Therefore, designing for repair should be prioritised over creating printed spare parts. If a product cannot be repaired at its part level, investing in the development of printed spare parts does not make sense. The case examples in Chapter 6 illustrate how a part can be designed to avoid these integrated, non-reversible assemblies, so individual parts can be replaced.

## 7.3 COMPARISON BETWEEN CONSUMER VS MANUFACTURER DESIGN PERSPECTIVE

One key difference between consumer and manufacturer design is when in the product lifecycle the printed spare parts are created. In Figure 7.3, the equivalent design and 3D-printing for Repair (3DPfR) processes have been mapped out against the product lifecycle. Here, the equivalent design process is placed at the beginning of the product lifecycle and the 3DPfR process at the end. With the equivalent design process, the manufacturer can enable printed spare parts at the start of the product lifecycle. This is especially beneficial for the design of original products, as discussed in Chapter 6. The 3DPfR process at the end of the product lifecycle limits the ability to adapt the part design but can be used to replace obsolete legacy parts. This process is accessible to both manufacturers and consumers, although the manufacturer benefits from increased design knowledge and industrial manufacturing equipment. When redesigning an existing product, the design of a printed spare part is similarly limited as with the 3DPfR process, even if the design process takes place at the beginning of the product lifecycle.

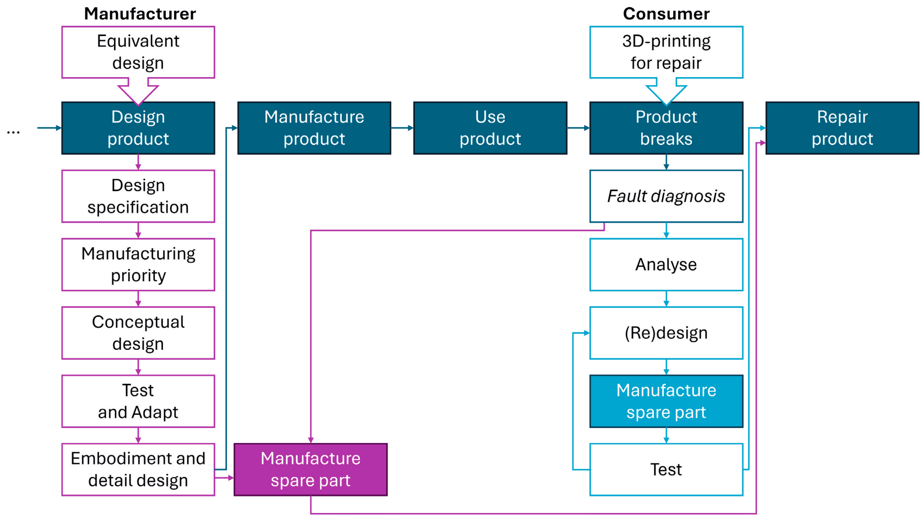



**Figure 7.3.** The equivalent design and 3D printing for Repair processes are mapped against the product lifecycle. The purple route represents repair with printed spare parts from a manufacturer design perspective and the light blue route represents the consumer design perspective.

While both design perspectives show potential, printed spare parts will likely be more feasible in an industrial setting. In Chapter 2, we estimated that between 8% to 29% of the repairs in repair communities could be suitable for additive manufacturing. In comparison, the general estimate of manufacturers was that 2% to 75% of their spare parts could be made with additive manufacturing, with most answers between 5% and 10% (Chekurov et al., 2018). While these numbers are generally comparable, if a manufacturer enables printed spare parts in the initial design of the product, this would significantly increase the number of parts that can be printed. Additionally, manufacturers have access to the original design files and industrial-level equipment, which further facilitates the process. However, even parts that are suitable for additive manufacturing would likely require some design attention. For legacy parts or products, it is a question of how much design time and effort the part is worth.

In comparison, a consumer might judge the required time, labour and costs of creating a printed spare part differently. With the right motivation and DIY mentality, consumers might enjoy the use of additive manufacturing in a way that a manufacturer wouldn't (Halassi et al., 2019). While not everyone with a broken product will be willing to spend the needed time and effort on this process, some consumers do. Within the 3D-printing community, the use of printed parts as spare parts is already relatively common. The knowledge and growth of this community suggest a significant potential for the open-source development of printed spare parts (Moilanen & Vadén, 2013; Rayna et al., 2021). Combined with movements such as Right to Repair, this might lead to an increase in part suitability in the context of consumer repair when looking beyond just the technical feasibility, especially for legacy products. However, a consumer might make unfavourable design or manufacturing choices due to their limited design knowledge and experience, as discussed in Chapter 2. To ensure that printed spare parts are reliable and safe, it is desirable to have some form of quality control and certification (Yoo et al., 2016). However, this will be challenging to achieve in the consumer design perspective.

## 7.4 3D-PRINTED SPARE PARTS IN A CIRCULAR ECONOMY

The availability of spare parts is key to the repairability of products. With additive manufacturing, spare parts can be made available after the initial production phase has ceased. Following the consumer design perspective, spare parts can even be made available for legacy products. The adoption of additive manufacturing for repair creates value chains that are shorter, simpler, and more localized (Gebler et al., 2014). Designs in the form of digital files can be easily shared, allowing products to be repaired on a more localised basis, potentially even on-site. This can significantly reduce the environmental impacts associated with transportation (Ford & Despeisse, 2016). The flexible design options and accessibility of additive manufacturing also allow for added value during repairs, even if this was not considered in the original product design (Sauerwein et al., 2019). This facilitates upgrading and refurbishing products in use with improved parts (Holmström & Gutowski, 2017). Furthermore, the use of additive manufacturing for product lifetime extension may encourage companies to adopt service-based business models that align with sustainability goals. This could help to separate social and economic value from the environmental impacts of production and consumption (Ford et al., 2015).



Still, a product that is not designed for repair may not be repairable, even if spare parts are available. What specific changes are needed in the product design depends on what specific additive manufacturing method is used. For most methods, the main barriers to printed spare parts are multi-material parts and integrated subassemblies in the product design, as discussed in Chapters 3–5. These design features overlap with those determining whether a part is suitable for repair, which include part accessibility, (dis)assembly, modularity, and standardisation (Dangal et al., 2022). Repairable products should allow for easy opening, and parts with higher failure rates should be the most accessible (Huang et al., 2016). When adhering to these repairability principles, non-reversible part connections are less likely to occur, facilitating the design of printed spare parts. Additionally, for both repair and printability, the degree of assembly modularity needs to be balanced. Integrating too many parts into bigger modules decreases disassembly time but increases costs (Dangal et al., 2022) and complicates printing. However, standardising product parts would reduce the need for printed spare parts. Managing the logistics for standardized parts is easier as these are less likely to become obsolete quickly, reducing the risk of overproduction, redundancy, and prolonged storage costs.

While the use of printed spare parts could extend the product's lifetime, the question remains whether this warrants the environmental impact of their production. Currently, injection-moulded spare parts are more environmentally friendly than printed ones, even with longer storage periods or potential overproduction (Hinze, 2025; Nijhof, 2025). This is mainly due to the energy consumption and material impact of additive manufacturing, as well as the number of printing iterations. From an environmental perspective, the overproduction and storage might for many parts be favourable over 3D-printing on demand (Hinze, 2025). This dissertation helps to reduce the impact of printed spare parts by giving designers more insight into what makes a part suitable and how to design suitable parts, thus lowering the number of printing iterations. The environmental impact of printed spare parts can be reduced further by choosing printing materials with a lower footprint or by favouring printing methods with a lower energy consumption.

## 7.5 CONTRIBUTIONS TO SCIENCE

The main contribution of this dissertation to science is its investigation into how the design of spare parts affects their printability. It demonstrates how the suitability of product parts for additive manufacturing can be estimated by comparing design requirements and manufacturing capabilities. This approach is innovative because most existing studies primarily focus on classifying suitable parts based on their geometry or the benefits to supply chain management (e.g., Chaudhuri et al., 2020; Frandsen et al., 2020; Haruna & Jiang, 2020; Khajavi et al., 2018; Knofius et al., 2016). While these studies acknowledge that technical feasibility is important in determining whether a part is suitable for additive manufacturing, they generally lack insight into how to assess it. As a result, it becomes difficult to identify what the design complexity and most significant design challenges will be. With the approach in this dissertation, designers can determine to what extent a part is suitable for additive manufacturing and which design aspects should be targeted to improve this.

This study also presents two new ways of designing printed spare parts. Through literature review, workshops, case studies, and practical examples, we developed the 3D-printing for Repair process and the equivalent design method with additional tools to support the designer. Other studies have explored the design of 3D-printed spare parts but presented a limited number of case studies to demonstrate the benefits of 3D-printed spare parts (e.g., Park, 2015;

Terzioğlu et al., 2016). None of these studies explores how to develop a systematic design approach for printed spare parts nor how designers should implement this. Additionally, the trade-offs in designing for both injection-moulding and additive manufacturing have rarely been investigated as most studies assume that 3D-printed spare parts involve replicating an existing (injection-moulded) part with additive manufacturing. As our research shows, this limits the opportunities for printed spare parts, so instead we explored how the original part design could be changed to enable the use of printed spare parts.

## 7.6 CONTRIBUTIONS TO SOCIETY

The main contribution of this dissertation to society is the practical tools it provides to enhance product repair. The 3D-printing for Repair process in Chapter 3 gives consumers a step-by-step approach to replacing broken or missing spare parts with 3D printing. We made this process more accessible to consumers through the 3D-printing for Repair guide (Bolaños Arriola et al., 2022), which also includes a series of instruction videos. While this approach is not the most suitable for large-scale production of spare parts, it can be used as a bottom-up approach to enhance product repairability and extend the lifetime of products. To enhance product repairability on a larger scale, we developed the equivalent design process in Chapter 6. This process can be used by the original product designer and manufacturer to design a product where the original part is produced through injection moulding and the spare part with additive manufacturing. This design process is further supported through the function identification tool and design ideation tool, both also presented in Chapter 6. With these tools, designers will have guidance on the intended part functionality and how to prevent or overcome the resulting design challenges.

Additionally, this dissertation also provides more insight into the capabilities of injection moulding and additive manufacturing for a comprehensive list of design requirements. While numerous online resources compare injection moulding and additive manufacturing, most are limited to geometrical differences and constraints. This comparison is challenging to supplement with insights from academic research, as most studies examine the capabilities of additive manufacturing on a lab scale rather than on an industrial level. The overview in Chapter 5 presents a comprehensive overview of industrial manufacturing capabilities, collected from a wide variety of sources. This overview will support designers and manufacturers in their understanding of the differences between injection moulding and additive manufacturing. Also, as the manufacturing capabilities are linked to the product requirements, it will be easier to apply them in the design process.

## 7.7 CONCLUSION AND RECOMMENDATIONS

To conclude, additive manufacturing is a promising method for producing spare parts. While it might not be a systematic solution for all parts and products, it can provide spare parts long after initial production has ceased or give legacy products a longer product lifetime. Currently, only a relatively small percentage of spare parts can be printed, but this could be addressed through careful design of the printed spare parts. In this dissertation, we have explored the capabilities of additive manufacturing and the various ways in which a printed spare part can be designed. By understanding the gap between the two manufacturing methods and adjusting the design accordingly, it becomes easier to produce 3D-printed spare parts. As additive manufacturing is flexible and rapidly evolving, it could be the missing link to enable long-term product repairs in the future.

There is still ample room for further research and development to ensure that printed spare parts are sustainable, viable and safe. Below, we discuss several possible directions.

First, the sustainability impact of printed spare parts must be reduced. The sustainability impact of additive manufacturing is generally high, so printed spare parts should be applied in a way that makes sense from an environmental point of view. We need more insight into what determines the sustainability impact of printed spare parts, for example through lifecycle analysis, to ensure their use is justified. Additionally, more sustainable design methods can be integrated into the design of printed spare parts, including design for repair, as suggested in this discussion. There is also potential for further development of additive manufacturing methods to enhance both their manufacturing capabilities and sustainability impact.

Secondly, the operational viability of printed parts should be optimised. While this dissertation analysed the technical feasibility of printed spare parts, various other factors need to be optimised before they can become viable from an operational point of view. Some form of quality control and certification should be established to ensure that a part adheres to the safety and performance regulations, either through the original manufacturer or additive manufacturing service providers. Additionally, as printed spare parts are likely significantly more expensive than original spare parts, their economic viability should be balanced compared to long-term storage. Besides certification and costs, other important factors include turnover time and logistics, legislation, liability, and intellectual property rights of printed parts. These factors have not been addressed in this dissertation but should be studied further to ensure the operational viability of printed spare parts.

## 7.8 REFERENCES

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

Bolaños Arriola, J., Van Oudheusden, A., Flipsen, B., & Faludi, J. (2022). 3D Printing for Repair Guide. In *3D Printing for Repair Guide*. https://doi.org/10.5074/t.2022.003

Chaudhuri, A., Gerlich, H. A., Jayaram, J., Ghadge, A., Shack, J., Brix, B. H., Hoffbeck, L. H., & Ulriksen, N. (2020). Selecting spare parts suitable for additive manufacturing: a design science approach. *Production Planning and Control*, *32*(8), 670–687. https://doi.org/10.1080/09537287.2020.1751890

Chekurov, S., Metsä-Kortelainen, S., Salmi, M., Roda, I., & Jussila, A. (2018). The perceived value of additively manufactured digital spare parts in industry: An empirical investigation. *International Journal of Production Economics*, *205*(September), 87–97. https://doi.org/10.1016/j.ijpe.2018.09.008

Chekurov, S., & Salmi, M. (2017). Additive Manufacturing in Offsite Repair of Consumer Electronics. *Physics Procedia*, *89*, 23–30. https://doi.org/10.1016/j.phpro.2017.08.009

Dangal, S., Faludi, J., & Balkenende, R. (2022). Design Aspects in Repairability Scoring Systems: Comparing Their Objectivity and Completeness. *Sustainability (Switzerland)*, *14*(14). https://doi.org/10.3390/su14148634

Ford, S., & Despeisse, M. (2016). Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. *Journal of Cleaner Production*, *137*, 1573–1587. https://doi.org/10.1016/j.jclepro.2016.04.150

Ford, S., Despeisse, M., & Viljakainen, A. (2015). Extending product life through additive manufacturing : The sustainability implications. *Global Cleaner Production and Consumption Conference, December*, 1–4. https://www.researchgate.net/publication/282075975_Extending_product_life_through_additive_manufacturing_The_sustainability_implications

Frandsen, C. S., Nielsen, M. M., Chaudhuri, A., Jayaram, J., & Govindan, K. (2020). In search for classification and selection of spare parts suitable for additive manufacturing: a literature review. *International Journal of Production Research*, *58*(4), 970–996. https://doi.org/10.1080/00207543.2019.1605226

Gebler, M., Schoot Uiterkamp, A. J. M., & Visser, C. (2014). A global sustainability perspective on 3D printing technologies. *Energy Policy*, *74*(C), 158–167. https://doi.org/10.1016/j.enpol.2014.08.033

Halassi, S., Semeijn, J., & Kiratli, N. (2019). From consumer to prosumer: a supply chain revolution in 3D printing. *International Journal of Physical Distribution and Logistics Management*, *49*(2), 200–216. https://doi.org/10.1108/IJPDLM-03-2018-0139

Haruna, A., & Jiang, P. (2020). A Design for Additive Manufacturing Framework: Product Function Integration and Structure Simplification. *IFAC-PapersOnLine*, *53*(5), 77–82. https://doi.org/10.1016/j.ifacol.2021.04.127

Hinze, J. (2025). *On-Demand or Stockpiled? A Prospective LCA of Additive Manufacturing vs. Traditional Spare Part Strategies* [Master's thesis]. Leiden University and Delft University of Technology.

Holmström, J., & Gutowski, T. (2017). Additive Manufacturing in Operations and Supply Chain Management: No Sustainability Benefit or Virtuous Knock-On Opportunities? *Journal of Industrial Ecology*, *21*, S21–S24. https://doi.org/10.1111/jiec.12580

Huang, J., Esmaeilian, B., & Behdad, S. (2016). DESIGN FOR EASE-OF-REPAIR: INSIGHTS FROM CONSUMERS' REPAIR EXPERIENCES. *Proceedings of the ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. http://proceedings.asmedigitalcollection.asme.org/pdfaccess.ashx?url=/data/conferences/asmep/90691/

Khajavi, S. H., Holmström, J., & Partanen, J. (2018). Additive manufacturing in the spare parts supply chain: hub configuration and technology maturity. *Rapid Prototyping Journal*, *24*(7), 1178–1192. https://doi.org/10.1108/RPJ-03-2017-0052

Knofius, N., Van Der Heijden, M. C., & Zijm, W. H. M. (2016). Selecting parts for additive manufacturing in service logistics. *Journal of Manufacturing Technology Management*, *27*(7), 915–931. https://doi.org/10.1108/JMTM-02-2016-0025

Laitala, K., Klepp, I. G., Haugrønning, V., Throne-Holst, H., & Strandbakken, P. (2020). Increasing repair of household appliances, mobile phones and clothing: Experiences from consumers and the repair industry. *Journal of Cleaner Production*, *282*, 125349. https://doi.org/10.1016/j.jclepro.2020.125349

Moilanen, J., & Vadén, T. (2013). 3D printing community and emerging practices of peer production. *First Monday*, *18*(8). https://doi.org/10.5210/fm.v18i8.4271

Nijhof, L. (2025). *To print or to purchase: a case study about the environmental impact of 3d printing for repair* [Master's thesis, Delft University of Technology]. https://resolver.tudelft.nl/uuid:f4f1da4c-702d-4a12-ae7f-22e21976f854

Park, M. (2015). Print to Repair: Opportunities and Constraints of 3D printing replacement parts. *PLATE: Product Lifetimes And The Environment*, 270–276. https://www.plateconference.org/print-repair-opportunities-constraints-3d-printing-replacement-parts/

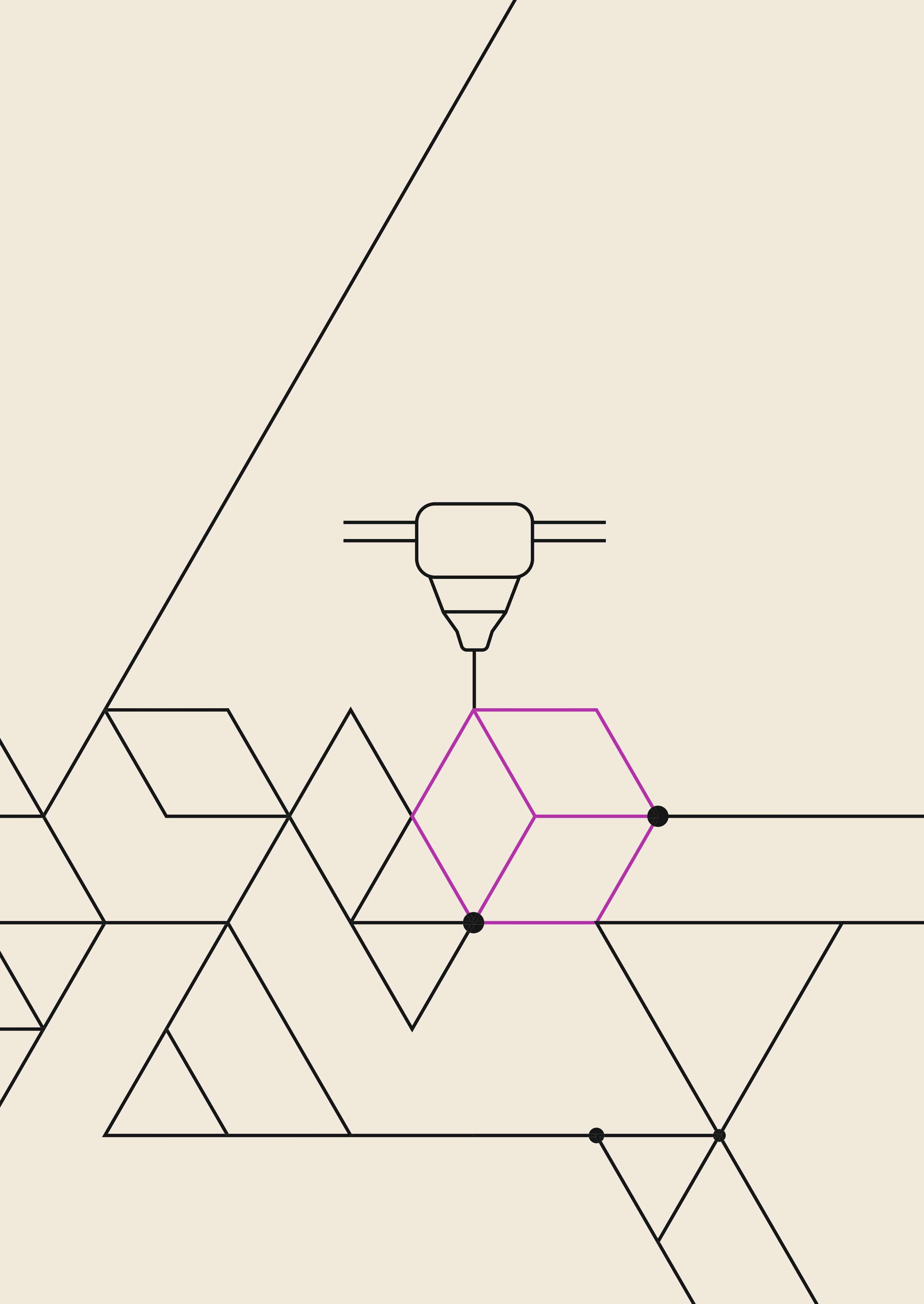
Rayna, T., Striukova, L., & Ludmila, S. (2021). Assessing the effect of 3D printing technologies on entrepreneurship. *Technological Forecasting and Social Change*, *164*, 120483. https://doi.org/10.1016/j.techfore.2020.120483ï

Sauerwein, M., Doubrovski, E., Balkenende, R., & Bakker, C. (2019). Exploring the potential of additive manufacturing for product design in a circular economy. *Journal of Cleaner Production*, *226*, 1138–1149. https://doi.org/10.1016/j.jclepro.2019.04.108

Tavares, T. M., Ganga, G. M. D., Godinho Filho, M., & Rodrigues, V. P. (2023). The benefits and barriers of additive manufacturing for circular economy: A framework proposal. In *Sustainable Production and Consumption* (Vol. 37, pp. 369–388). Elsevier B.V. https://doi.org/10.1016/j.spc.2023.03.006

Terzioğlu, N., Brass, C., & Lockton, D. (2016). 3D Printing for Repair : A Paradigm Shift in Fixing Our Relationships with Things. *Sustainable Innovation*, *November*(21st international conference), 274–281.

Yoo, B., Ko, H., & Chun, S. (2016). Prosumption perspectives on additive manufacturing: Reconfiguration of consumer products with 3D printing. *Rapid Prototyping Journal*, *22*(4), 691–705. https://doi.org/10.1108/RPJ-01-2015-0004



# APPENDICES

# LIST OF PUBLICATIONS

## Publications included in this dissertation

### Conference paper

Samenjo, K.; van Oudheusden, A.; Bolaños, J.; Flipsen, B.; Faludi, J. Opportunities For 3D-Printable Spare Parts: Estimations From Historical Data. In Proceedings of the 4th PLATE Virtual Conference, Limerick, Ireland, 26–28 May 2021.

### Journal article

van Oudheusden, A., Arriola, J. B., Faludi, J., Flipsen, B., & Balkenende, R. (2023). 3D Printing for Repair : An Approach for Enhancing Repair. *Sustainability*, *15*(6), 51–68. https://doi.org/https://doi.org/10.3390/su15065168

### Conference paper

van Oudheusden, A.; Buijserd, A.; Doubrovski, Z.; Flipsen, B. Feasibility of On-Demand Additive Manufacturing of Spare Parts. In *PLATE 2023: 5th PLATE Conference*; Aalto University: Espoo, Finland, 2023; pp. 1129–1136.

### Journal article

van Oudheusden, A., Faludi, J., & Balkenende, R. (2024). Facilitating the Production of 3D-Printed Spare Parts in the Design of Plastic Parts: A Design Requirement Review. *Sustainability (Switzerland)*, *16*(21). https://doi.org/10.3390/su16219203

### Journal article (submitted)

van Oudheusden, A., Faludi, J. & Balkenende, R. (2025). Equivalent design: functionally equivalent parts through injection moulding and additive manufacturing. *Submitted to Cleaner Manufacturing and Technology.*

## Contributions outside of this dissertation

### 3D Printing for Repair Guide

Bolaños Arriola, J.; Van Oudheusden, A.; Flipsen, B.; Faludi, J. (2022). *3D Printing for Repair Guide*; TU Delft OPEN Publishing: Delft, The Netherlands, ISBN 9789463665414. https://doi.org/10.5074/t.2022.003

### Journal article (Preprint)

Dangal, S., Ritzen, L., van Oudheusden, A., Faludi, J. and Balkenende, R. Modeling Disassembly and Reassembly Times (Dart) for Assessing Repairability. *Preprint.* http://dx.doi.org/10.2139/ssrn.5163542

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# ABOUT THE AUTHOR

Alma van Oudheusden was born on November 29th, 1996 in Delft, the Netherlands. She studied Industrial Design Engineering at Delft University of Technology, where she uncovered her passion for both sustainability and research. During her studies, she followed all available courses on sustainability and did a research project on the recyclability of composite materials. She also worked as an intern at the sustainability department at Dutch railways company NS, where she graduated in 2020 on the topic of circularity in the Dutch train. After her graduation, she stayed on at Industrial Design Engineering as a PhD in the Circular Product Design group. While having no prior experience with 3D-printing whatsoever, she dived headfirst into the topic of 3D-printing for repair. During her PhD, she refined both her research and design skills and developed practical tools and methods to support the design of printed spare parts. Her work has also been used for an instruction guide and 3D-printing workshop, as well as various bachelor and master projects. She also has a filament printer and resin printer at home which have taught her a lot on what is and isn't possible and, most of all, the importance of bed levelling. In her free time, Alma likes to hike the mountains and forest, together with her boyfriend and her dog.