How to design spare parts for stereolithography to replace injection moulded parts

Development of a form factor optimisation guide

Master thesis

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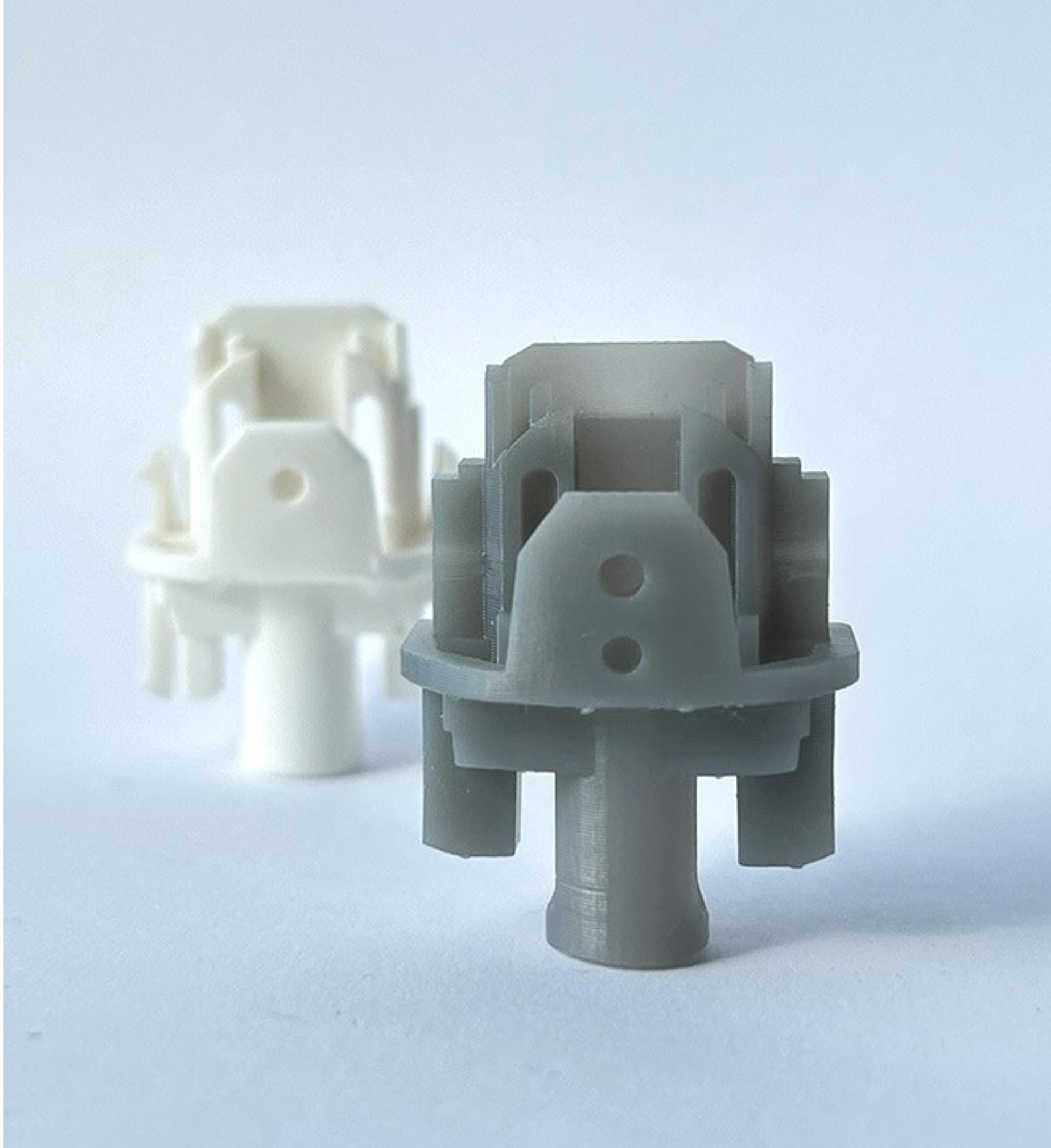

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Preface and acknowledgements

Long before I started my studies Industrial Design Engineering, I already loved tinkering with products or any material that I turn into something. Over the past few years, a passion for sustainability and engineering has grown on top of my love for tinkering. Not a week goes by without me fixing something in or around the house, repairing a product or 3D printing a new project. Recently, I have even joined Repair Café Delft as a repair volunteer.

When this graduation project (Appendix A) came across my path, I was immediately attracted to it. It fit my workstyle and the topic was something I was passionate about: the embodiment design phase of product development, working towards improved repairability.

I would like to express my gratitude to my chair Ruud Balkenende, my mentor Zjenja Doubrovski and my ‘bonus-mentor’ Alma van Oudheusden for their constructive feedback during the project. The discussions we had were a valuable asset to my project that gave me the confidence to continue striving forward. I also want to thank my friends and family who have supported me along the way.

Hopefully you feel as passionate about repairing products as I do after reading this report. Enjoy!

Abstract

The goal of this thesis was to provide designers guidance in designing their yet-to-be designed products that contain injection moulded parts in a way that allows for interchangeable, functionally equivalent spare parts produced with additive manufacturing in the future. The project was scoped to stereolithography as the additive manufacturing technology, focusing on geometrical and mechanical aspects of product design. The result of the thesis is a newly developed guide, referred to as the 'form factor optimisation guide' (Figure 1). This guide was developed by analysing literature and conducting various case studies.

Two newly developed approaches are part of the form factor optimisation guide, referred to as the 'geometry-based part coupling approach' and the 'form factor definition approach'. A designer can compose a product architecture map using the geometry-based part coupling approach to map the relationships of coupled parts. Parts are considered coupled when they influence each other's geometry. The product architecture map, along with the list of requirements, is used to define the 'form factor' of a part. This form factor is the design space and non-design space for the part's geometry. Using the form factor, the designer can optimise the part for production with injection moulding and stereolithography. It may occur that the form factor does not allow the designer to cope with the limitations of each manufacturing technology. In this case, 'reciprocity' is applied. Reciprocity is the term that is used to describe the process of going back and forth between the designs of coupled parts and their requirements. Reciprocity is applied until the form factor allows for interchangeable, functionally equivalent parts produced with injection moulding and stereolithography.

Key words: spare part, product design, repair, additive manufacturing, stereolithography, injection moulding, form factor, product architecture.

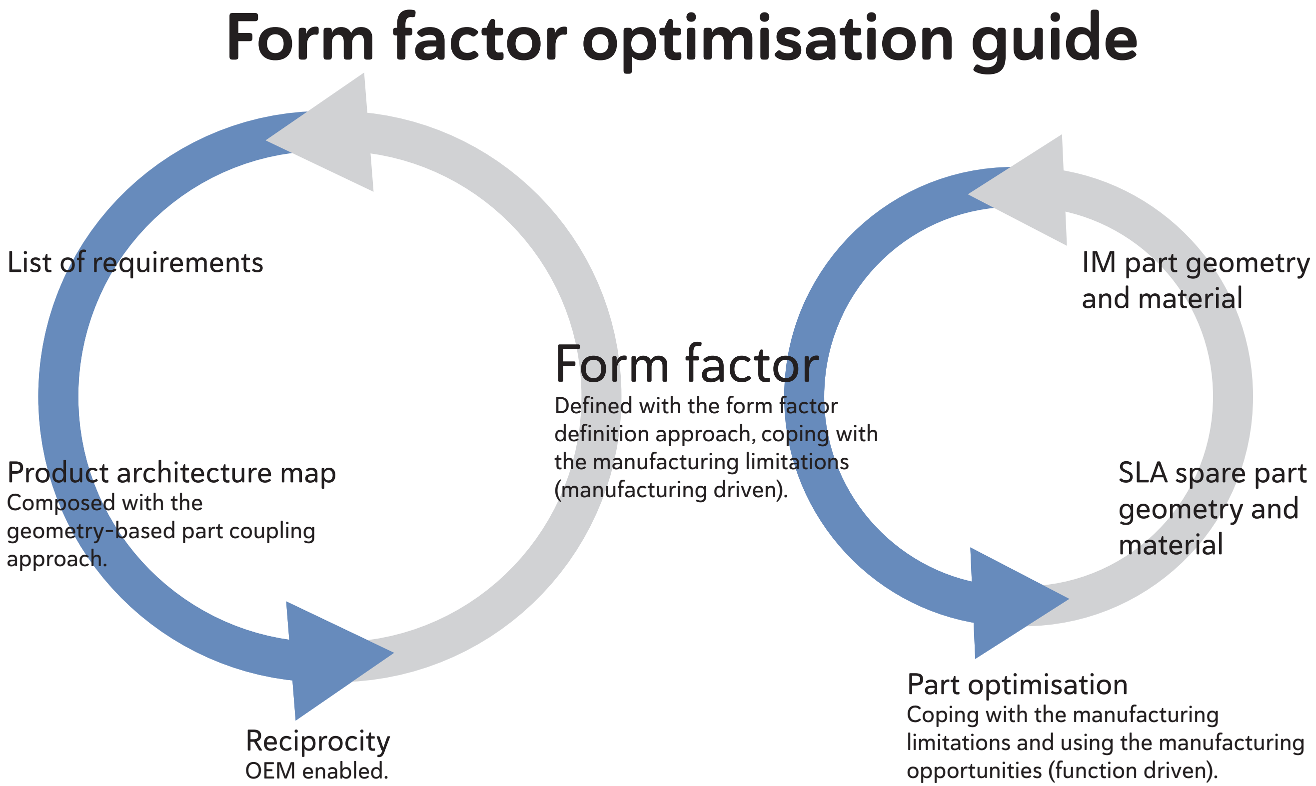

Figure 1: The newly developed form factor optimisation guide.

Glossary

Table 1 contains all abbreviations that were used throughout the research, along with their meaning.

Table 1: All abbreviations used throughout the research and their meaning.

Abbreviation	Meaning
2D	Two-dimensional
3D	Three-dimensional
AM	Additive manufacturing
CAD	Computer aided design
FDM	Fused deposition modelling
IM	Injection moulding
MoSCoW method	Must, Should, Could and Won't have's: four priority indicators in a list of requirements
OEM	Original equipment manufacturer
PA6(GF30)	Polyamide, glass filled for 30%
PC	Polycarbonate
PCB	Printed circuit board
PLA	Polylactic acid
PP	Polypropylene
PU	Polyurethane
RQ	Research question
SLA	Stereolithography
SLS	Selective laser sintering

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1 | Introduction

Repairing products and original equipment manufacturers (OEM) providing the spare parts to do so is slowly becoming standard in counteracting the ongoing climate crisis through circularity and sustainability (Tischner & Stasiuk, 2023). European Union regulations in the ‘Right to Repair directive’ require companies to provide spare parts over a prolonged period for common household products (European Parliament, 2024), for up to 10 years within 15 working days for several product categories (European Commission, 2019). Besides, there are various other regulations and frameworks, such as:

- The French repairability index, released in 2021 (Ministère de la Transition écologique et de la Cohésion des territoires, 2021), replaced by a new sustainability index from 2025 onwards (Ministère de la Transition écologique et de la Cohésion des territoires, 2024) for various product categories.
- The Belgium framework law (Hellebaut, 2024).
- iFixit’s repairability score framework (iFixit, 2024).
- European Union ecodesign and energy labelling regulations from 2025 for phones and tablets to provide spare parts and manuals for 7 years after the last distribution of the product (Ganapini, 2023) (Spiliotopoulos et al., 2022).

In various repairability scoring frameworks and legislation, spare part availability is a substantial factor. For example, spare part availability counts for 20% in the French repairability index (HOP, 2024) and for 10% in iFixit’s repairability score framework (iFixit, 2024). In the European Commission’s Joint Research Centre’s framework, the score for the spare part parameter is based on availability over time, delivery time, recommended retail price, target groups and part interface (Cordella et al., 2019).

Injection moulding (IM) is the most used technology to mass-produce plastic parts (Wang et al., 2013). Once the tooling has been made and set up, parts can be produced quickly for a relatively low price per part, as long as the investment costs can be spread amongst many parts. It is thus mostly used for producing large batch sizes (Franchetti & Kress, 2017). Another manufacturing method, namely additive manufacturing (AM), also referred to as 3D printing, is mostly advantageous in small batch sizes due to the absence of required upfront investment (Klahn et al., 2015).

Producing spare parts with additive manufacturing could be an interesting way for companies to avoid having to store and ship many spare parts for years whilst still complying with the aforementioned guidelines. Producing small batch sizes of spare parts on-demand using a conventional method like IM results in a larger carbon footprint and higher supply chain costs compared to using AM (Li et al., 2017). With AM, costs for producing and storing production tools are avoided (Lindemann et al., 2015). However, parts that are manufactured with one technology (for example with IM) cannot always be copied and manufactured with a different technology (for example with AM), because of the different manufacturing capabilities (van Oudheusden et al., 2024). Besides, there are other limitations such as post-processing that complicate the use of AM to produce spare parts for IM parts (Chekurov et al., 2018).

1.1 | Problem statement

This graduation project contributes to existing research by providing designers guidance in designing their yet-to-be designed products that contain IM parts in a way that allows for interchangeable, functionally equivalent spare parts produced with AM in the future. Limited research is published on how to produce spare parts with alternative manufacturing methods, such as AM. Buijserd (2022) and Arriola (2022) have set up some guides that can help consumers in the production of spare parts, based on the original product. However, research by van Oudheusden et al. (2023) shows that the process is rather complex and limitations are formed as parts need to fit into the original, existing product. Tackling the issue from an OEM perspective could be a solution and was explored in this graduation project.

1.2 | Research questions and method

The research was scoped to focus on the geometry and mechanical requirements of plastic IM parts in consumer electronics products. The focus on geometry and mechanical requirements was chosen because they are design aspects that need to be considered in many plastic parts. Furthermore, these are aspects closely related to part performance and the fit in a product, which are challenges in the process of manufacturing spare parts with AM (van Oudheusden et al., 2023). The focus on consumer electronics was chosen because consumer electronics are often brought to Repair Cafés for repair (Repaircafe, 2018) (Postma, 2015) and are thus a product category for which it is logical to produce spare parts. They are also widely available to use for analysis in case studies.

The project was scoped to one AM technology to explore in Chapter 2. This is not necessarily the most suitable AM technology to use for spare part production, just the technology that is explored. The technology is selected through a list of criteria. The technologies are assessed based on literature review and explorative prototyping. Materials compatible with the selected technology are also analysed on how closely they match the plastics found in the consumer electronics products of the case studies.

Chapter 3 explores the differences in the manufacturing process and capabilities of IM and the selected AM technology that need to be considered in the design process to result in interchangeable, functionally equivalent parts manufactured with either technology. This is done through literature review and a case study. The following research question (RQ) was answered:

RQ1: "Which differences in the manufacturing capabilities and process of IM and the selected AM technology need to be considered in the design of interchangeable, functionally equivalent parts manufactured with either technology?"

Two more research questions were answered. These provide professional designers guidance in the development process of interchangeable, functionally equivalent parts with IM and AM. Simply stated, these discuss what the available design freedom is, followed by a way to deal with the differences in the manufacturing processes that are stated in Chapter 3.

RQ2: "Which design approaches can help a designer determine the available geometric design freedom to produce interchangeable, functionally equivalent parts with the selected AM technology and IM?"

RQ3: "How can designers use the available design freedom as a means to produce interchangeable, functionally equivalent parts, produced with the selected AM technology and IM?"

RQ2 was answered in Chapter 4 and RQ3 was answered in Chapter 5. The research questions were answered through literature review and various case studies. Methods were gathered from literature. These were further built on by gathering practical insights in a research-through-design approach (Stappers & Giaccardi, 2014) with case studies on parts of consumer electronics products.

Chapter 6 and 7 contain two case studies in which the insights from the research questions were applied. This was done to indicate if the gathered insights actually provide what is required to design interchangeable, functionally equivalent parts manufactured with IM and AM.

2 | Manufacturing technology selection and material analysis

In order to create focus and have a defined list of design and manufacturing parameters to work with, a specific AM technology was selected in section 2.1. Afterwards, in section 2.2, a material analysis was executed, for the materials compatible with the selected AM technology.

2.1 | AM technology selection

The goal of this section was to select one AM technology to work with to narrow down the scope of the project. This does not imply that this AM technology is necessarily the best solution to use for spare part production. It is just that it is the method that was explored.

2.1.1 | Method for AM technology selection

A pre-selection of three AM technologies was formed. This pre-selection was based on the work by van Oudheusden et al. (2024) because the research paper presents a table of data that assesses three AM technologies based on design requirements. The full table can be found in Appendix B.

A list of criteria was set up to justify the choice for selecting an AM technology. This list of criteria, along with the explanation and reasoning for the criteria can be found in Table 2. One of the AM technologies of the pre-selection was selected based on the criteria in Table 2. Technologies that could not fulfil one or more of the criteria were eliminated from the selection.

Table 2: Criteria for the AM technology selection.

Criterion	Explanation
Part quality and performance	The AM technology must be able to produce consumer electronics parts of adequate quality with the machine available for this research. The development in AM technology means that parts can now be produced with final-use quality (Gibson et al., 2021). Since the focus is on aiding professional designers (OEM), it is assumed that they have access to machines that can produce parts with final-use quality. Therefore, there must be reasonable certainty that the part production reliability in this research is not influenced by the available machine. The project was scoped to assess part quality and performance based on the following seven design requirements that van Oudheusden et al. (2024) addressed. Sufficient data was available regarding the capabilities of the AM technologies from the pre-selection on these design requirements: • Shape • Detail • Accuracy and tolerances • Surface finish • Strength • Flexibility • Elasticity
Costs	Although budget is not a high priority, this is a graduation thesis with limited budget. Therefore, the costs of working with the AM technology must be affordable.
Manufacturing availability	Because this is a graduation thesis with a limitation of 100 working days and several part iterations are made, parts should be manufacturable and ready within a reasonable timeframe (five working days roughly) after finishing the computer aided design (CAD) file. This can be either by ordering the parts online or manufacturing them on the available machines at Delft University of Technology.

Data was collected to assess the AM technologies from the pre-selection on the criteria in Table 2. Data was obtained through literature research and explorative prototyping. The goal of the explorative prototyping was to see how well the AM technologies were able to replicate the geometry of the IM part, as a way to assess the technology on the 'part quality and performance' criterion.

A steam iron was chosen for explorative prototyping as irons are a consumer electronics product commonly brought to Repair Cafés (Postma, 2015) and thus have a variety of parts that likely break down often. Specifically, a Tefal iron (Tefal, 2024) (Figure 2) was used for the explorative prototyping. The Tefal iron FV1711 was chosen because it had a large variety of plastic IM parts with mechanical requirements that may be hard to implement in AM (van Oudheusden et al., 2024). A part of the Tefal iron FV1711 was chosen based on the geometric complexity. The part had features protruding from all six sides of the part and small geometry. Furthermore, it is a part that keeps all components of an operating mechanism together. Therefore, the part quality for the mechanism was important for the part to function properly.

The part was measured with callipers and modelled in the SolidWorks 2023 CAD software. The CAD file was exported as an .stl file, to be able to import it in the slicer software for AM production. The gcode for production with FDM was generated by slicing the model in Cura. The part was 3D printed using the gcode on an Ultimaker 2+ printer with white PLA filament. The part was also produced using a Formlabs Form 3+ printer with Tough 1500 resin.

The geometry of the printed parts was compared to the original IM part. The intention when making the CAD model was to create a 1:1 geometric copy, to eliminate the influence that the CAD model has on the comparison of the AM parts and the original IM part. In this comparison, the ability of the AM technologies to replicate the geometry of the IM part was evaluated, as a way to assess the technology on the 'part quality and performance' criterion.

2.1.2 | Results of AM technology selection

A wide range of AM technologies exists (Figure 3), but not all AM technologies were considered for this analysis. The AM technologies analysed in the work by van Oudheusden et al. (2024) are stereolithography (SLA, a form of vat polymerization), selective laser sintering (SLS, a form of powder bed fusion) and fused deposition modelling (FDM, a form of material extrusion). Due to the detailed list of information in the work regarding the manufacturing capabilities of these technologies, these three AM technologies formed the pre-selection of considered AM technologies.

SLA, SLS and FDM were chosen by van Oudheusden et al. (2024) for their availability and the quality of parts that they provide (Mika & Pei, 2023). This means that all three AM technologies were candidates to meet the 'part quality and performance' and 'manufacturing availability' criteria from Table 2.

Figure 2: Tefal iron FV1711.

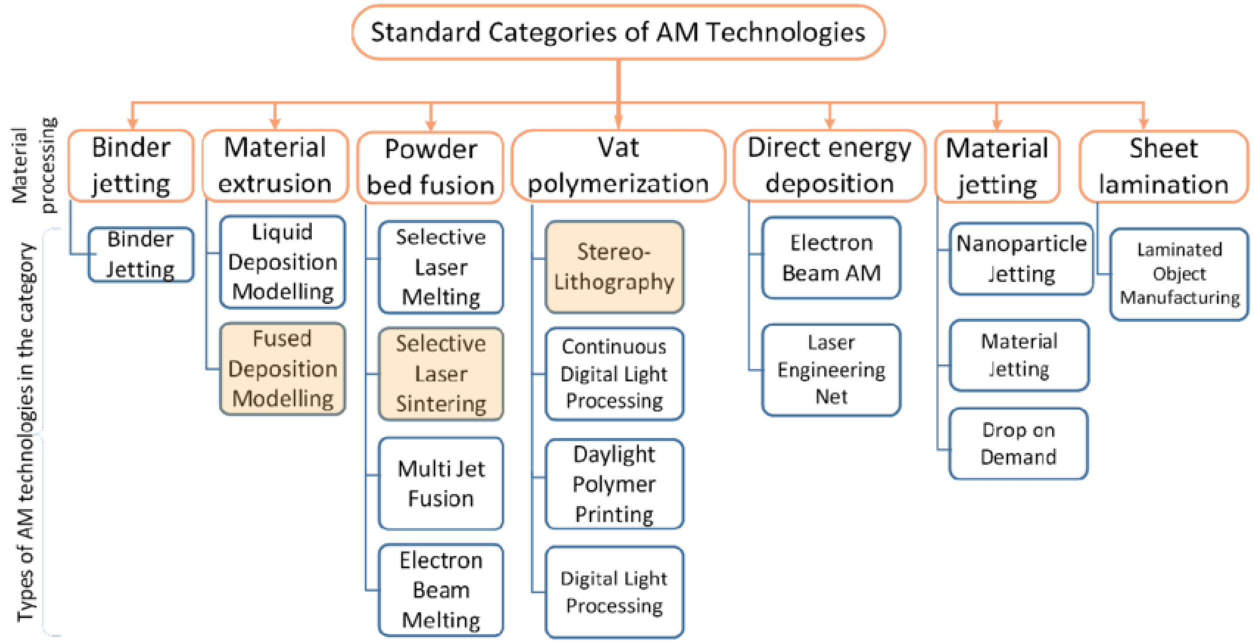


Figure 3: Standard categories of AM technologies (Adugna et al., 2021), with the AM technologies from the pre-selection highlighted.

An extract of the data of SLA, SLS and FDM by van Oudheusden et al. (2024) was composed in Table 3. The extract only presents the data for the seven mentioned design requirements that were used to assess the AM technologies on the 'part quality and performance' criterion.

Table 3 shows that none of the three AM technologies from the pre-selection were able to meet all seven design requirements at the level of IM. SLA is slightly inferior to IM in strength and elasticity. SLS only matches IM in shape and accuracy and tolerances. FDM only matches IM in accuracy and tolerances and flexibility. Furthermore, FDM is considerably inferior in strength.

Since none of the three AM technologies were able to meet all seven design requirements at the level of IM, the AM technologies were compared to each other. Table 3 shows that SLA and SLS match IM in shape, accuracy and tolerances, strength and elasticity. SLA outperforms SLS in all other design requirements. SLA and FDM match IM in accuracy and tolerances and flexibility. SLA outperforms FDM in all other design requirements. From the comparisons between the AM technologies can thus be concluded that SLA performs the best out of the three AM technologies in the seven design requirements of the 'part quality and performance' criterion.

Table 3: An extract of manufacturing capabilities by van Oudheusden et al. (2024), condensed to just the rows used to assess the AM technologies on the part quality and performance criterion. "The footnotes indicate the following data quality for that requirement: 1 = High-quality data, 2 = Medium-quality data ... 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" (van Oudheusden et al., 2024).

Design Requirement	Injection Moulding (IM)	Stereolithography (SLA)	Selective Laser Sintering (SLS)	Fused Deposition Modeling (FDM)
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]
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]
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]

SLA and FDM printers are widely available at Delft University of Technology. More than twenty Ultimaker 2+ printers are available for FDM printing and at least three Formlabs Form 3(+) printers are available for SLA printing. Producing parts was free of charge. This means SLA and FDM meet the 'costs' and 'manufacturing availability' criteria from Table 2. Because an SLS printer is not available at Delft University of Technology, SLA and FDM were the two AM technologies that were preferred as options to use. SLS was thus eliminated as an AM technology to use.

An aspect of the 'part quality and performance' criterion is the capability of the machines available for this research. To test the abilities of the available Formlabs Form 3+ SLA printer and Ultimaker 2+ FDM printers to produce a part with adequate quality and performance, some design iterations were made on the 'steam setter holder' of the Tefal iron FV1711 (Tefal, 2024) (Figure 4).

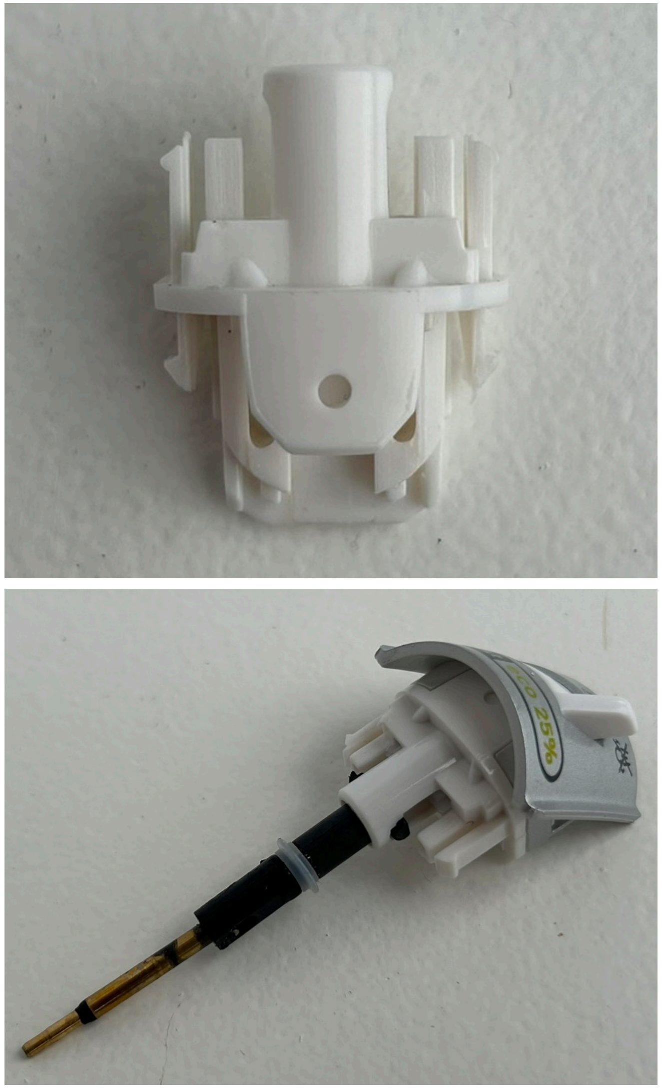


Figure 4: The steam setter holder of the Tefal iron FV1711 is an important part to make the steam setting mechanism work properly, with many mechanical connections to moving parts. This means that the part quality is of high importance.

Despite various tries (Figure 5), the part could not be produced with FDM in the desired quality. Although the support placement, part orientation and layer height parameters were altered in an effort to produce the part reliably, the part was still not at an OEM level. Due to layer separation and the complexity of the part with features in all directions, the part was too weak to be considered an acceptable copy produced with FDM. Furthermore, lots of post-processing was required in the form of removing support material and the surface finish was of low quality. FDM is thus not a suitable option with the available machines for this project, due to the lack of part quality and performance.

SLA is able to print parts at high quality due to the resolution in which it is able to print (Wu et al., 2023). This was demonstrated in the model made with SLA (Figure 6). All features were printed as modelled in the CAD model and not prone to breaking because the layers adhered to each other sufficiently. The available Formlabs Form 3+ SLA printer was thus able to print a part that is geometrically complex without issues.

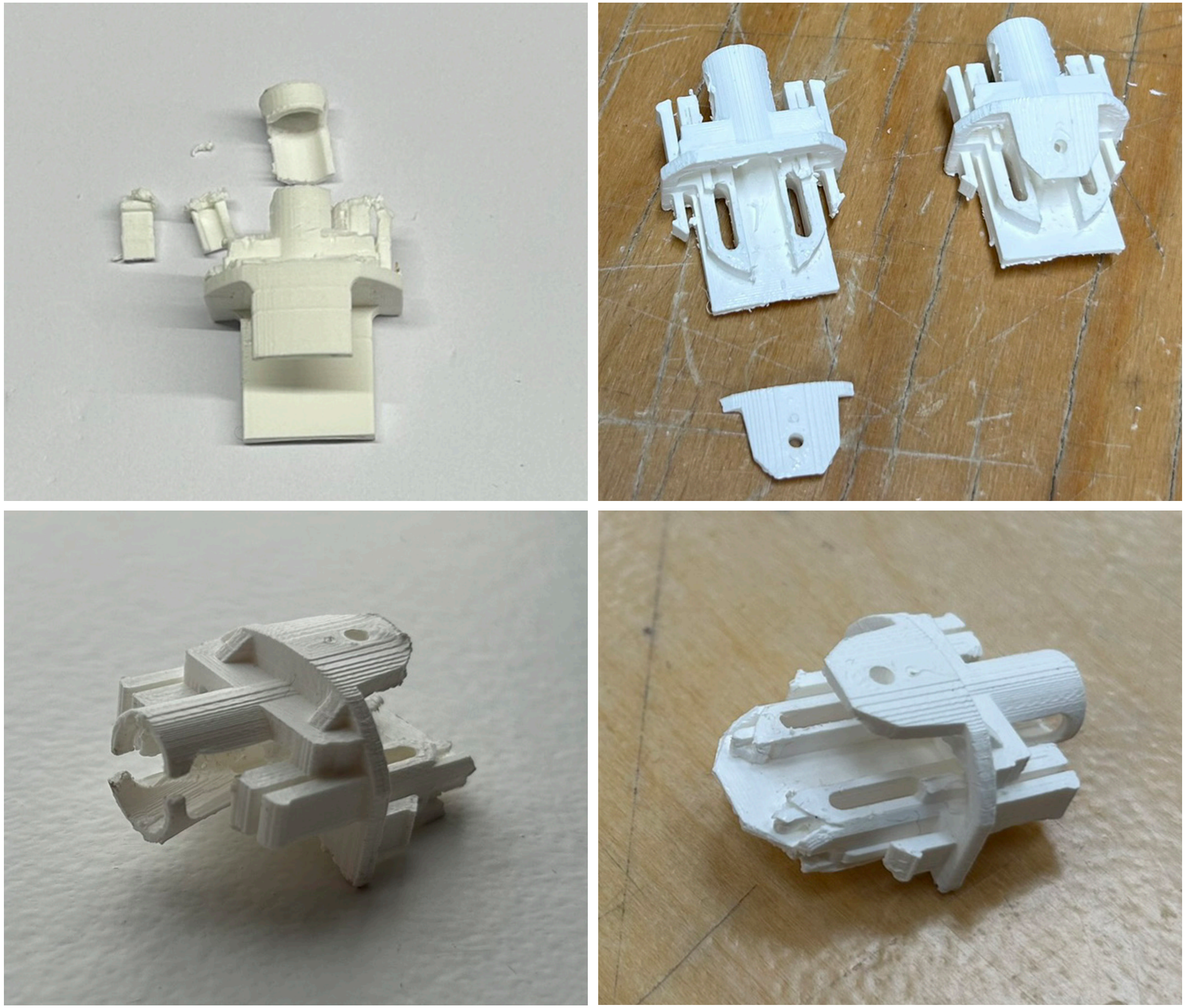


Figure 5: By adjusting the manufacturing parameters in multiple iterations, the steam setter holder could be produced with an Ultimaker 2+ FDM printer, but not to a reliable, adequate level.

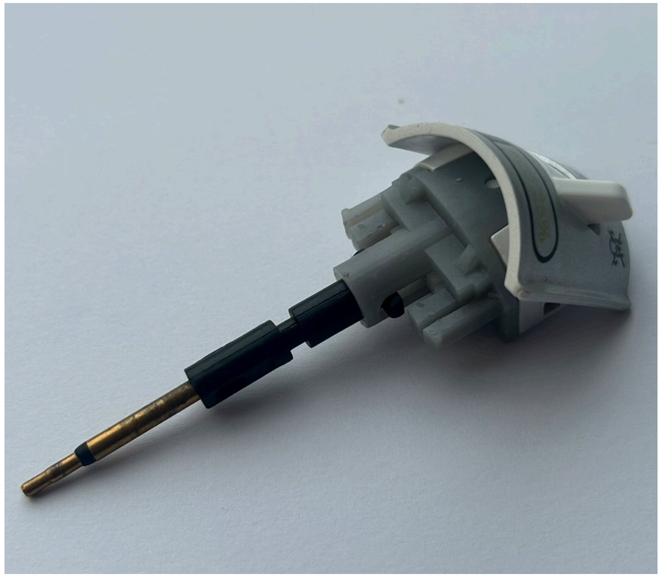


Figure 6: The steam setter holder produced with a Formlabs Form 3+ SLA printer.

2.1.3 | Conclusion of AM technology selection

The goal of this section was to select one AM technology to work with. From the analysis of SLA, SLS and FDM can be seen that SLA is able to perform best on the criteria mentioned in Table 2. SLA printers are available and affordable to use. The available SLA printer was able to produce a part that is geometrically complex without issues. SLA is also superior to SLS and FDM in matching IM on the mentioned design requirements that were used to assess the ‘part quality and performance’ criterion. This means that for the remainder of the report, SLA was selected as the AM technology to explore, making use of a Formlabs Form 3+ printer.

2.2 | Material analysis

Based on the choice for SLA as the selected AM technology from section 2.1 and the availability of a Formlabs Form 3+ printer for this project to produce parts with SLA, materials were researched that are compatible with this machine.

The research focused on the fact that an IM part and its interchangeable, functionally equivalent AM spare part are produced with technologies with different specifications and how to deal with that. SLA is still an evolving technology with new, improved resins being released (Formlabs, 2025b). Therefore, the research does not focus on creating a guide on how to design spare parts specifically with the currently available materials and their properties. Nevertheless, a material analysis was performed to be able to make a judgement on when to use which material and how to select it.

2.2.1 | Method for material analysis

To find out what materials can be found in plastic consumer electronics parts, three consumer electronics products were disassembled (Appendix C). The chosen products are a Tefal iron, a Ferm cordless drill and a Bosch hand blender. These products were chosen because they contain plastic components that are used mechanically. Furthermore, they were available to use in the research.

A list of the available materials that are compatible with the Form 3(+) printer was gathered from the website of the printer’s manufacturer, Formlabs. The materials were assessed based on the list of criteria composed in Table 4. Several part samples were ordered to be able to investigate the material in real-life before using the materials for the production of prototypes.

2.2.2 | Results of material analysis

Formlabs does not offer a full dataset of every material compatible with the Form 3+ printer. However, they do provide the ultimate tensile strength, tensile modulus and elongation at break, so this is the data on which the 'Ability to meet consumer electronics part design requirements' was determined.

The majority of the plastic IM parts from the three disassembled products were made from PP, PC and PA6(GF30) (Appendix C). From the Granta EduPack 2024 R2 database (level 3), the data in Table 5 was gathered.

Table 6 shows the list of material options considered at the time of selecting the materials, which are all resins, along with the manufacturer's material information (Formlabs, 2024b). Some options were not considered, most of them due to being named 'elastic' or 'silicone', which would not be able to meet the 'Ability to meet consumer electronics part design requirements' criterion. Based on the criteria in Table 4, the resins were assessed based on the costs and production process criteria in Table 6. Afterwards, the resins were evaluated on their match with the material properties of PP, PC and PA6(GF30) of Table 5, respectively in Table 7, Table 8 and Table 9.

Table 4: Criteria for the SLA material selection.

Criterion	Explanation
Costs	Although budget is not a high priority, this is a graduation thesis with limited budget.
Production process	The shelf life of the material should at least last the duration of the project (5 months). Furthermore, there should be no need for specialty (safety) equipment outside of regular personal protective equipment.
Ability to meet consumer electronics part design requirements	Most case studies in the report were performed on parts from the three products that were disassembled (Appendix C). It was desired to somewhat match the mechanical properties of the prototypes to the original IM part material properties. Therefore, the mechanical properties of the material should fall within the range of material properties of the IM parts in the disassembled products.

Table 5: PP, PC and PA6(GF30) material data, gathered from the Granta EduPack 2024 R2 database, to allow for evaluation of the resins on the 'ability to meet consumer electronics part design requirements' criterion.

Material	Ultimate tensile strength	Tensile modulus	Elongation at break
PP (unfilled, random copolymer, high flow)	26-50 MPa	0.824 - 1.02 GPa	112 - 483 %
PC (low viscosity, moulding and extrusion)	62.7 - 72.4 MPa	2.32 - 2.44 GPa	110 - 150%
PA6(GF30)	111 - 180 MPa	5.34 - 6.66 GPa	5.14 - 7.4 %

Table 6: Formlabs (Formlabs, 2024b) resins scores on the costs and production process. Green = matches the criterion, yellow = does not comply, but could be acceptable, red = does not match the criterion.

Resin	Costs per 1L resin tank	Production process
General purpose (white resin 4.1)	$149	No foreseeable issues
Flame retardant	$249	No foreseeable issues
High temperature	$199	No foreseeable issues
PU rigid 1000	$149	Shelf life 1 month, humidity cure chamber required but not available
PU rigid 650	$149	Shelf life 1 month, humidity cure chamber required but not available
Rigid 10k	$299	No foreseeable issues
Rigid 4000	$229	No foreseeable issues
Tough 1500	$149	No foreseeable issues
Tough 2000	$149	No foreseeable issues

Table 7: Formlabs (Formlabs, 2024b) resins scores on the material properties of PP. Green = matches the criterion, yellow = does not comply, but could be acceptable, red = does not match the criterion.

Resin	Ultimate tensile strength	Tensile modulus	Elongation at break
General purpose (white resin 4.1)	53 MPa	2.367 GPa	8%
Flame retardant	41 MPa	3.1 GPa	7.1%
High temperature	49 MPa	2.8 GPa	2.3%
PU rigid 1000	35 MPa	0.92 GPa	80%
PU rigid 650	34 MPa	0.67 GPa	170%
Rigid 10k	88 MPa	11 GPa	0.7%
Rigid 4000	69 MPa	4.1 GPa	5.3%
Tough 1500	33 MPa	1.5 GPa	51%
Tough 2000	46 MPa	2.2 GPa	48%

Table 8: Formlabs (Formlabs, 2024b) resins scores on the material properties of PC. Green = matches the criterion, yellow = does not comply, but could be acceptable, red = does not match the criterion.

Resin	Ultimate tensile strength	Tensile modulus	Elongation at break
General purpose (white resin 4.1)	53 MPa	2.367 GPa	8%
Flame retardant	41 MPa	3.1 GPa	7.1%
High temperature	49 MPa	2.8 GPa	2.3%
PU rigid 1000	35 MPa	0.92 GPa	80%
PU rigid 650	34 MPa	0.67 GPa	170%
Rigid 10k	88 MPa	11 GPa	0.7%
Rigid 4000	69 MPa	4.1 GPa	5.3%
Tough 1500	33 MPa	1.5 GPa	51%
Tough 2000	46 MPa	2.2 GPa	48%

Table 9: Formlabs (Formlabs, 2024b) resins scores on the material properties of PA6(GF30). Green = matches the criterion, yellow = does not comply, but could be acceptable, red = does not match the criterion.

Resin	Ultimate tensile strength	Tensile modulus	Elongation at break
General purpose (white resin 4.1)	53 MPa	2.367 GPa	8%
Flame retardant	41 MPa	3.1 GPa	7.1%
High temperature	49 MPa	2.8 GPa	2.3%
PU rigid 1000	35 MPa	0.92 GPa	80%
PU rigid 650	34 MPa	0.67 GPa	170%
Rigid 10k	88 MPa	11 GPa	0.7%
Rigid 4000	69 MPa	4.1 GPa	5.3%
Tough 1500	33 MPa	1.5 GPa	51%
Tough 2000	46 MPa	2.2 GPa	48%

The results in Table 6, Table 7, Table 8 and Table 9 show that none of the available resins fully match all criteria from Table 4. Only the general purpose, Tough 1500 and Tough 2000 resin match both the 'costs' and 'production process' criteria. None of the materials that were analysed fall within all three of the acceptable mechanical property ranges from Table 5. Table 7 shows that the PU rigid resins most closely match PP, matching at least two of the mechanical properties. Table 8 shows that the Tough 2000 resin is the only resin that scores acceptably on all three material properties of PC. Table 9 shows that the Rigid 4000 resin most closely matches the material properties of PA6(GF30).

Four samples were ordered from Formlabs (Figure 7). These included samples made with general purpose, Tough 1500 and Tough 2000 resin, because these match at least two of the criteria from Table 4. Even though the PU rigid resins do not meet the 'production process' requirement, one of the two materials was selected (PU rigid 1000) just to check one more sample that matches at least two of the mechanical property ranges from Table 5.

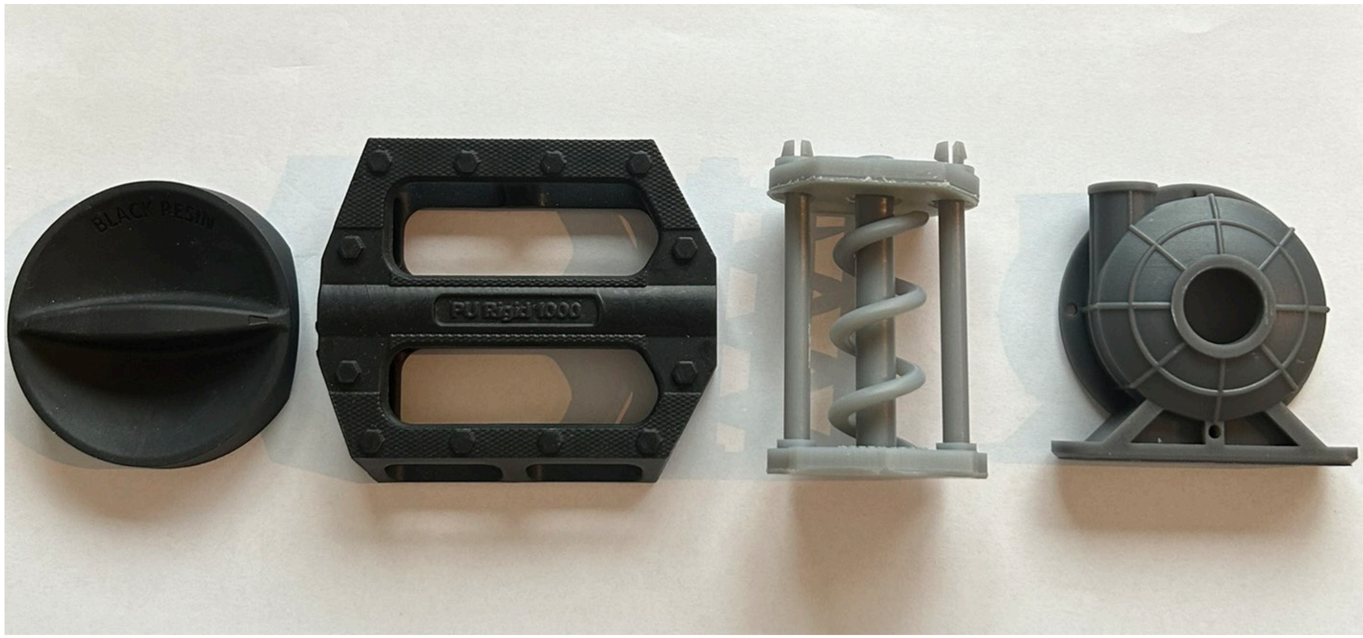


Figure 7: Four samples were ordered to investigate how the resins turn out to be. From left to right: general purpose, PU rigid 1000, Tough 1500 and Tough 2000.

The stiffness of the samples was investigated by pushing and pulling the parts by hand, looking for deformations of the material. The Tough 2000 resin sample did not deflect at all under the pushing load of a hand (male, age 24). The general purpose and PU rigid 1000 resin samples deflected a maximum of 2 mm elastically under the same pushing load. The Tough 1500 resin sample deflected elastically over various lengths under the pushing load, ranging anywhere from 2-40 mm depending on the feature of the part. The Tough 1500 resin thus seems the most appropriate resin of these four resins to use in applications where deflection is required. A major limitation of this research was that the parts do not have the same geometry. Therefore, the geometry of the part influenced the results of the investigation of the stiffness of the material.

2.2.3 | Conclusion of material analysis

None of the materials that Formlabs offers fully match the material properties of PP, PC or PA6(GF30), which were found during the disassembly of three consumer electronics products. This indicates that the availability of identical material properties for IM and SLA cannot be assumed in the design process of functionally equivalent parts. Of the analysed materials, PU rigid resins most closely match PP. Tough 2000 resin most closely matches PC and Rigid 4000 resin most closely matches PA6(GF30). Considering the costs and production process requirements, it may be more preferable to use general purpose, Tough 1500 or Tough 2000 resin.

3 | Identifying differences between IM and SLA

3.1 | Method for identifying differences between IM and SLA

If an already designed IM part could be manufactured with SLA, resulting in an interchangeable, functionally equivalent spare part, no redesign of the part or spare part is required. That is not always possible though (Lindemann et al., 2015). It may also not be desirable, for instance for optimisation purposes. This chapter serves to answer the following research question:

RQ1: "Which differences in the manufacturing capabilities and process of IM and SLA need to be considered in the design of interchangeable, functionally equivalent parts manufactured with either technology?"

The insights from this research are used to shape the proposed design process in Chapter 5. Furthermore, these found differences in the manufacturing capabilities and process of IM and SLA are used to form the case studies in Chapter 6 and 7. This is done to explore how the found differences can be dealt with in the design process of interchangeable, functionally equivalent parts produced with IM and SLA.

Section 3.1 states the method that was used to gather the composed list of differences in the manufacturing capabilities of IM and SLA, with the results in section 3.2. The chapter is concluded in section 3.3.

To understand the differences in the manufacturing process and capabilities of IM and SLA that need to be considered in the design process, both technologies were analysed through literature review. First, a general understanding of both technologies was established. Then, data was collected on the manufacturing capabilities, the design rules and process of working with both manufacturing methods. An IM expert at a Dutch design agency was consulted to validate the insights.

Only aspects that have to be considered for either IM or SLA were included in the composed list of differences in the manufacturing process and capabilities. Aspects that have to be considered for both technologies in the design process are not included, because they are expected to influence the geometry of the part and spare part equally. This overlap of design aspects is visualised in Figure 8.

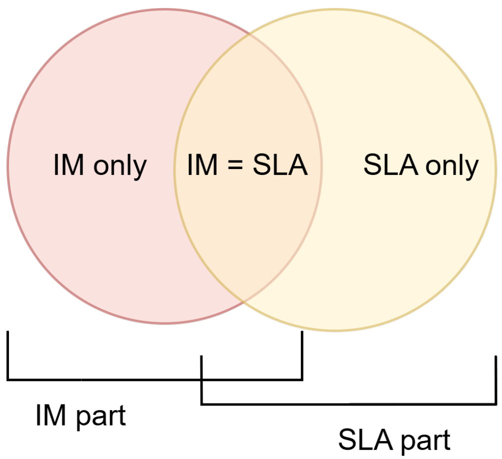


Figure 8: Although there may be overlap in working with IM and SLA, the differences are expected to end up resulting in different designs for IM and SLA.

The analysis differentiates between opportunities and limitations of IM and SLA. A manufacturing aspect was categorised as an opportunity if the technology provides the designer design extra design freedom due to its capabilities. A manufacturing aspect was categorised as a limitation if the technology limits the design freedom of a part. Limitations were sorted in three categories:

- **Limiting requirements:** A design rule must be applied to the part's design to allow for production with the technology. Here it is interesting to know if this requirement for one technology can also be manufactured with the other technology, to determine the overlap in manufacturing capabilities. For example, draft angles are a requirement (and therefore a design rule) for production with IM (Rees, 2001). Draft angles are not required for production with SLA, but draft angles can be applied to the parts in order to achieve geometric copies if this is desired.
- **Manufacturing defects:** An undesired defect is left on the part by one of the manufacturing technologies. These are mostly unavoidable, but a part can be designed in such a way that the defects are hidden as well as possible from the user during regular use. For example, the punch marks left on an IM part by the ejector pins of an IM machine are a defect that may be desirable to hide from the user.
- **Potential issues:** A technology is not able to produce parts with the same specifications as the other technology. For example, SLA

cannot produce parts as large as IM can (van Oudheusden et al., 2024).

A case study was performed to validate how the limitations of an existing IM part translate to SLA with the same geometry. To do so, creating a geometric copy of an IM part with SLA was attempted. The chosen part for the case study was selected because it represented a wide selection of the found limitations of IM. The part was analysed on its features and modelled as closely as possible in SolidWorks 2023 CAD software. An important note regarding this research is that this approach is different compared to the OEM perspective. The CAD model was reverse engineered based on the single available part, whereas an OEM could use the CAD file that is available to them. After finishing the CAD model, it was manufactured using a Formlabs Form 3+ SLA printer with Tough 1500 resin.

A taxonomy of geometrical part structures was developed. This was done to explore if such a structured approach to part geometry would help in identifying complex part structures of IM parts that pose problems to production in SLA. The full method that was used to develop the taxonomy can be found in Appendix D.

3.2 | Results of identifying differences between IM and SLA

3.2.1 | Differences in limitations and opportunities of IM and SLA

In IM (Figure 9), hot plastic is injected into a mould to create a part. When the part has cooled down sufficiently, the movable parts of the mould move out the way and ejector pins eject the part. After this, the mould closes back up and the process is repeated to manufacture the next part (Rosato & Rosato, 2012).

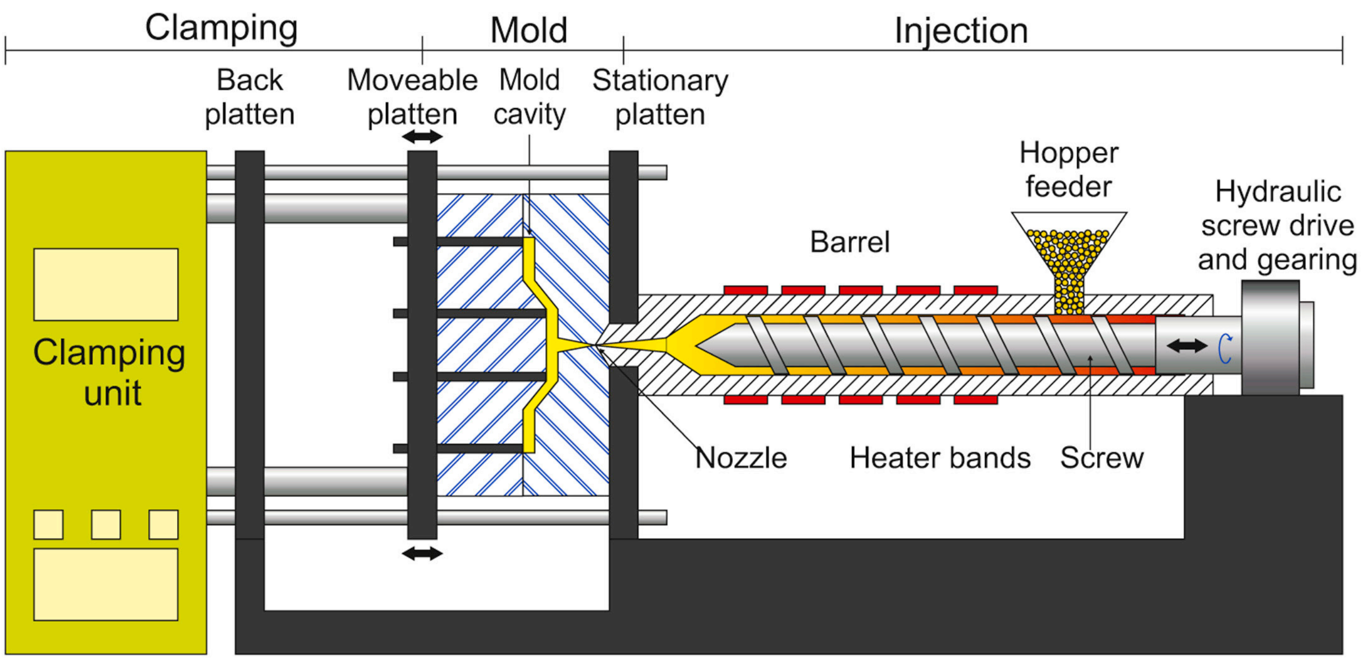


Figure 9: A simplified diagram of an injection moulding machine (Khosravani et al., 2019).

SLA is a manufacturing technology that cures a photosensitive resin with UV light to create a part (Diegel et al., 2019) (Figure 10). The CAD model of the part is split up in layers. The SLA printer is programmed per layer where to cure resin and where not to cure resin. After finishing one layer, the stage with the model attached moves vertically to the position for the next layer. This process is repeated until the part is completely formed. Afterwards, the part needs to be removed from the stage, washed to remove excess resin and fully cured (Formlabs, 2024a).

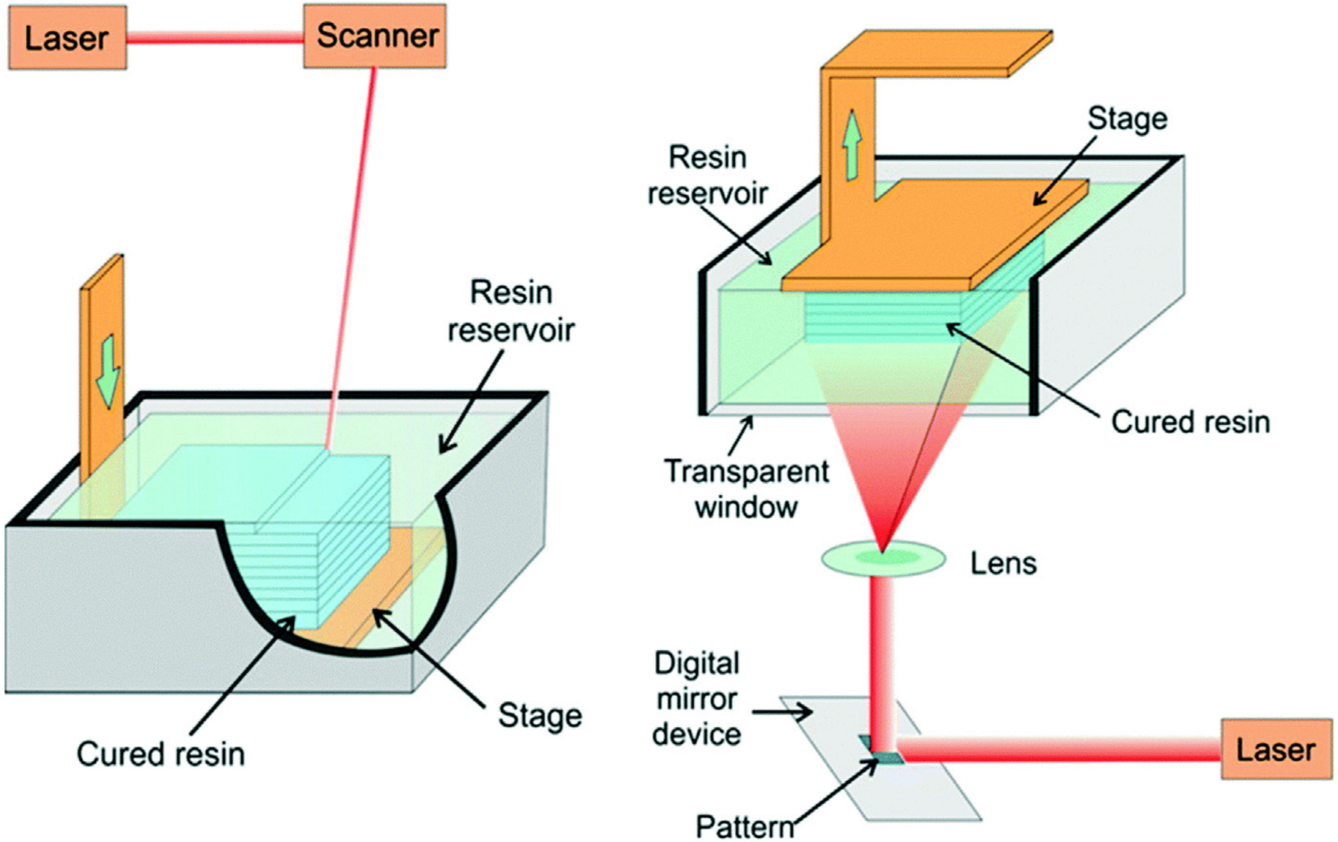


Figure 10: A simplified diagram of an SLA printer (Moritz & Maleksaeedi, 2018). Multiple orientations are possible, with the part being printed whilst standing or hanging on the stage.

Because IM and SLA are based on different working principles, the technologies have different limitations in what parts they can produce. These limitations, regarding geometry and mechanical requirements, were sorted in three categories: limiting requirements, manufacturing defects and potential issues. The limitations that apply uniquely to IM or SLA are listed in Table 10. These limitations are aspects that need to be considered by designers in the design process of interchangeable, functionally equivalent parts manufactured with IM and SLA. An approach on how to deal with the limitations of each manufacturing technology is explored in Chapter 5.

Table 10: Limitations of IM and SLA.

Type of limitation	**Applies uniquely to manufacturing technology (IM / SLA)**	**Aspect**	**Elaboration**
Limiting requirements, mandatory for manufacturing	IM (Rees, 2001)	Equal wall thicknesses	Equal wall thicknesses are used to prevent warping and sink marks.
		Ribs	Ribs can be used for extra stiffness without compromising equal wall thicknesses.
		Draft angles	Draft angles of at least 1 degree must be applied to models to get the part out of the mould. Undercuts can be produced with slides, but this complicates the manufacturing process.
		Material indication	Parts are often labelled with their manufacturing date and material.
	SLA	Support	Using support material for geometries that have overhangs is recommended. Furthermore, there is a fine balance in the ‘pulling game’, making sure that the part stays stuck to the print bed without staying stuck to the bottom of the resin tank (Formlabs, 2025d).
		Escape holes	Escape holes need to be added to parts in case of hollow segments in the part to let uncured resin drain out (VoxelMatters, 2017).
Manufacturing defects	IM (Rees, 2001)	Injection point mark	A mark is left on the part where the molten plastic gets injected in the mould. Hot runners can be used to avoid most of the mark.
		Punch marks	Marks are left on the part by the ejector pins that push the part out of the mould.
		Parting line	The mould design determines where the parting line is placed. The parting line is where the various parts of the mould come together.
		Flashing	Some plastic can get in between the parts of the mould and leave undesired plastic 'films' attached to the part.
		Weld lines	Lines are left on the product where multiple flows of plastic come together.
	SLA (Formlabs, 2025d)	Support removal	Support material must be removed from the model after production, which could leave marks and increases the amount of required post-processing.
		Uncured resin	Some resin may be left on the part if it the part is cured without proper cleaning, leading to incorrect geometry.

Table 10 (continued).

Type of limitation	Applies uniquely to manufacturing technology (IM / SLA)	Aspect	Elaboration
Potential issues	IM (van Oudheusden et al., 2024)	Minimum feature size	IM has a minimum feature size of 0.4-0.6 mm compared to 0.1-0.4 mm for SLA.
		Minimum wall size	IM parts have a minimum wall size of 0.8-1.2 mm compared to 0.1-0.4 mm for SLA.
		Accuracy and tolerances	Tolerances for parts are as low as 0.025 mm, compared to 0.01-0.03 mm for industrial SLA machines.
	SLA	Material choice	The material choice is limited to a small number of available photosensitive resins (Wu et al., 2023).
		Surface finish	The Ra can be as low as 0.4 micrometre, compared to 0.012 micrometre for polished finishes in IM (van Oudheusden et al., 2024).
		Strength	Parts can have a tensile strength around 88 MPa (Formlabs, 2024b), compared to 120 MPa for IM, and are near-isotropic, but not fully isotropic like IM (van Oudheusden et al., 2024). Parts may become brittle over time and when exposed to light and heat in sunlight (Formlabs, 2025a).
		Elasticity	Elongation at break is limited to 300%, compared to up to 1780% for IM (van Oudheusden et al., 2024).
		Maximum part size	The maximum part size possible is 736 x 635 x 533 mm, compared to 1220x1220 mm for IM (van Oudheusden et al., 2024).

Table 10 shows that the limiting requirements of IM are related to various aspects of the manufacturing process, partially related to correct cooling of the part and the way the part is ejected. The manufacturing defects of IM are all related to the injection and ejection stage of the process. The potential issues of IM are caused by the fact that SLA is able to produce slightly smaller geometry. The limiting requirements and manufacturing defects of SLA are related to support material and uncured resin. The smaller number of available materials compared to IM means that the range of available material properties for SLA is limited, which forms potential issues.

The mentioned limitations from Table 10 can also be seen as opportunities for production with the other technology. For example, undercuts are generally avoided in IM. SLA can create hollow structures (Diegel et al., 2019). Therefore, an opportunity for SLA is that parts with undercuts can be designed without facing issues in manufacturing, allowing for more complex parts. Another example is the fact that SLA parts are ideally designed in a way that avoids the need for support, to reduce the amount of post-processing that is required. This does not have to be considered for IM.

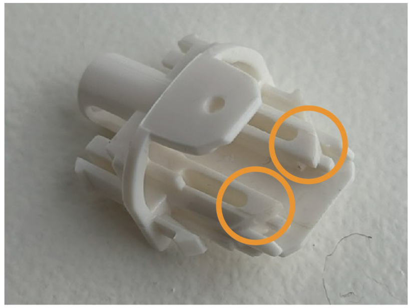
3.2.2 | Case study to explore translation of IM to SLA

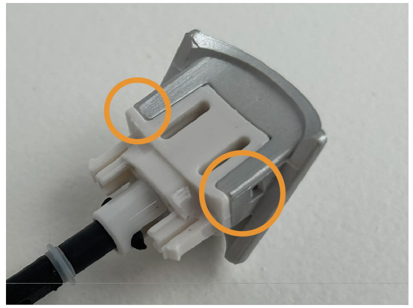
To validate how the limitations of an existing IM part translate to SLA using the same geometry, a case study was performed on the steam setter holder of the Tefal FV1711 iron (Figure 4), as also shown in Chapter 2. This part was chosen from the IM parts from the three disassembled products found in Appendix C, because it contains all limiting requirements and manufacturing defects of IM stated in Table 10, apart from the material indication.

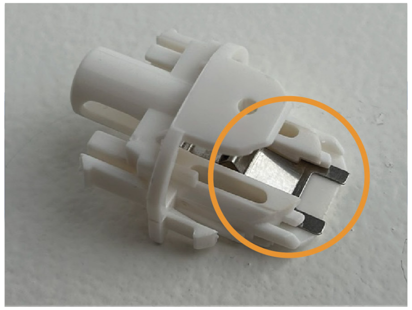
It was expected to print poorly based on the fact that:

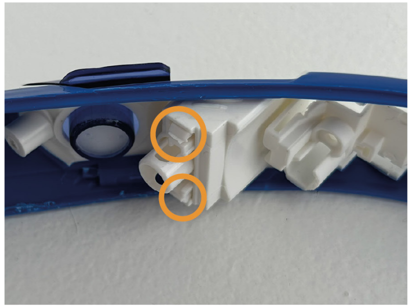
1. It is a complex structure with small features on all six sides of the part. This means it has unsupported features regardless of the print orientation that need support material. This support material needs to be removed from places that are hard to reach.
2. It has nine critical mechanical connections (Figure 11), all dependent on the tolerances of the part. Though the tolerances of SLA are theoretically good, any production error could result in jamming of the mechanism.


Clearance fit with the turn button axle

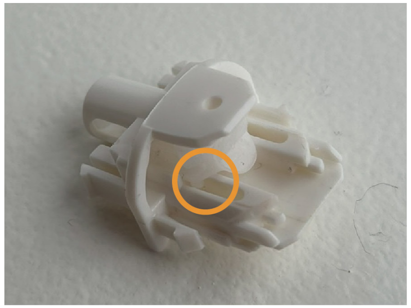

Clearance fit with the turn button perimeter

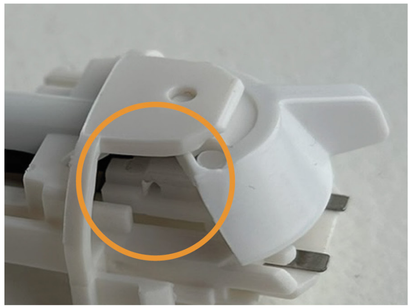

Transition (snap) fit with the top cover


Transition fit and depth stop with the leaf spring


Transition (snap) fit at the bottom of the top shell


Clearance fit in the upper half of the top shell


Clearance fit with the slider


Height-restricted clearance fit with the slider and turn button

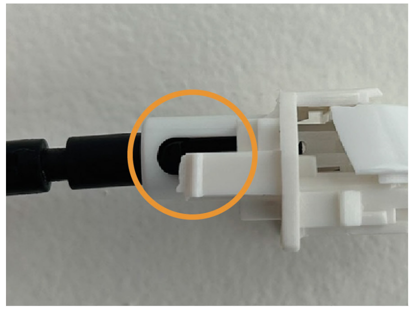

Clearance fit and rotation stop with the black shaft

Figure 11: The relation of the steam setter holder to its surrounding parts. The distiguishment of the types of fits is elaborated on in Chapter 4.1.

As can be seen in Figure 12, the steam setter holder was printed adequately with SLA. The mechanism operates, fully using the range of movement of the shaft and turn button. Furthermore, the two snap fits operate with different forces as required and the material's look & feel are of similar quality as the IM part. SLA was able to manufacture the equal wall thicknesses, ribs and draft angles (including undercuts) that were included in the CAD model because these are limiting requirements for production with IM. For production with SLA, these features were not required but could still be produced. This shows that SLA was able to closely replicate the IM part. The material indication was not included in the CAD model and thus also not manufactured. The manufacturing defects of IM are not applicable to SLA and thus do not appear in the model.

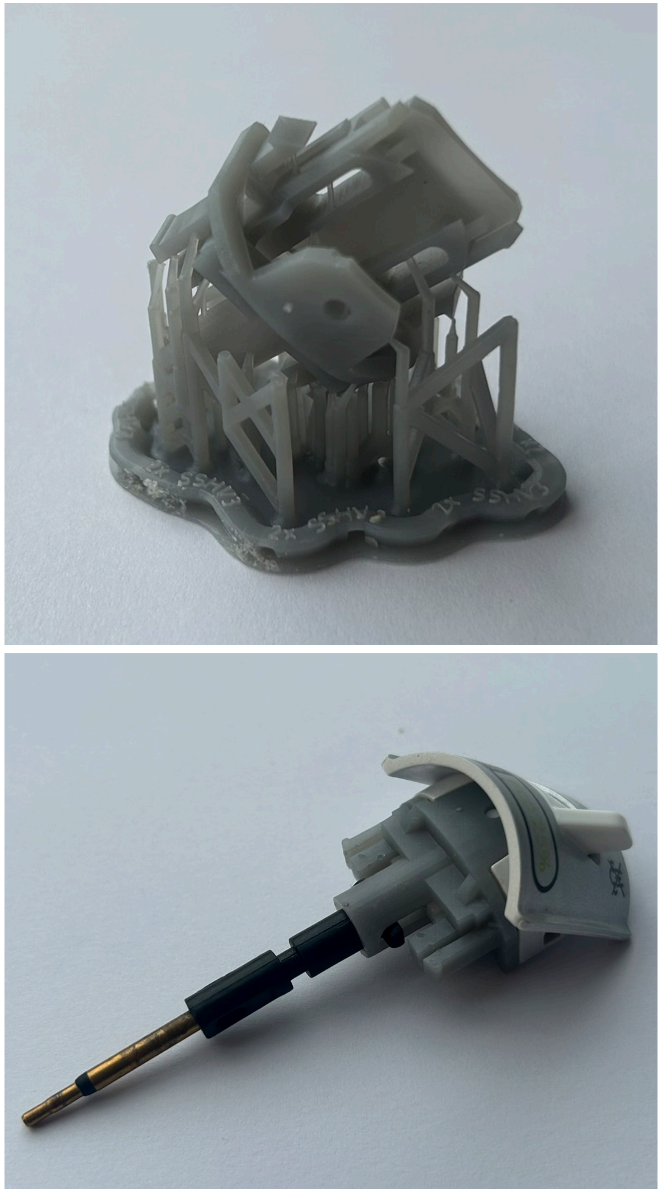


Figure 12: The steam setter holder produced with SLA.

To explore if a structured, categorisation approach to part geometry would help in identifying complex part structures that pose problems to production in AM, a taxonomy was composed. However, the taxonomy was deemed not needed for SLA spare parts since SLA could produce the complex part structure of the steam setter holder. The full process of the development of the taxonomy can be found in Appendix D.

Disregarding numerous factors caused by the lack of OEM knowledge and access to files and equipment, there are still some factors of the part that are not optimised or uncertain. For a more elaborate analysis of the part performance and optimisation of the manufacturing process, the following factors should be further researched:

- Optimisation of the time required for support removal.
- The amount of support required, to reduce the carbon footprint of the part.
- Uncertainty of the part performance over time due to plastic deflection of the snap fits, caused by creep and being under constant load.
- Uncertainty of the part performance over time due to exposure to UV light and becoming brittle (Formlabs, 2025a).

3.3 | Conclusion of identifying differences between IM and SLA

In this chapter, the differences in the manufacturing process and capabilities of IM and SLA that need to be considered in the design process to result in interchangeable, functionally equivalent parts manufactured with either technology were investigated. Table 10 presents a composed list of the limitations of the manufacturing process and capabilities of IM and SLA. In the design process, (OEM) designers need to consider these differences between IM and SLA in their design solution to end up with interchangeable, functionally equivalent parts that can be manufactured with IM and SLA. The limitations of SLA are mostly related to support, uncured resin and the smaller number of available materials compared to IM. In general, SLA is able to produce smaller, more complex geometry than IM. Furthermore, the way in which an IM machine operates, leaves various manufacturing defects and requires various measures to ensure correct cooling of the part to prevent warping.

Based on the results of the case study (section 3.2.2) on a complex part, it seems that SLA can be used to manufacture geometric copies of most parts originally designed for IM. The complexity of the part structure seemingly does not matter. However, optimisation of the part and its manufacturing process, based on the opportunities and manufacturing capabilities presented in Table 10, is still possible.

4 | Determining design freedom

The fact that SLA is seemingly able to produce most IM parts as a 1:1 geometric copy is positive. Every part with a non-identical spare part adds part variety and thus increases the number of possible product configurations. When identical geometry is not sufficient to achieve functional equivalence, for example in mechanical strength due to a difference in material properties, a redesign is required. And even when an identical geometric copy suffices, a redesign may be desirable to optimise the part for production with AM. The non-identical spare part must still be interchangeable with the regular part though, requiring geometric design freedom. Therefore, in this chapter, the following research question is answered:

RQ2: "Which design approaches can help a designer determine the available geometric design freedom to produce interchangeable, functionally equivalent parts with SLA and IM?"

To answer this question, two research directions were explored. The first research direction concerned ways to determine by which neighbouring components a part's geometry is influenced (section 4.1). Then, in section 4.2, an exploration was executed to define what design space is left by these components (section 4.2).

This research only focused on redesigning one part at a time for spare part production, as opposed to redesigning an entire product. Therefore, it was assumed that a part's design is determined by its original function and the design freedom for the part is determined by its neighbouring parts that are already set. In the OEM design process, there may be more design freedom, if the geometry of parts is not set yet.

4.1 | Geometry-based part coupling approach

This section explores a newly developed approach, referred to as the 'geometry-based part coupling approach'. The approach explores a way to define by which neighbouring parts a part's geometry is influenced and in what way. Knowing this is the first step to determining the available geometric design freedom to change a part's geometry. The second step, which is explored in section 4.2, builds on this information.

Section 4.1.1 covers the literature on which the geometry-based part coupling approach is based. Section 4.1.2 contains the method that was used to compose the approach and section 4.1.3 contains the result, in which the approach was applied to a case study. Section 4.1.4 concludes section 4.1.

4.1.1 | Literature regarding product architecture maps and geometric part coupling

In literature, methods were gathered for mapping geometric relations between components: the product architecture. The existing methods were gathered to be combined in the newly developed geometry-based part coupling approach. The aspects of the methods that provide information regarding the available geometric design freedom for spare part production compose the list of requirements for the geometry-based part coupling approach.

The function structure method by Ulrich (1995) (Figure 13) use the main functions of a product as the starting point. The function structure indicates what has to become a functional element within the product, what the external entities are and the links between the two. The product configuration scheme by Begelinger et al. (1999) (Figure 14) indicates the possible configurations of a product. This is done by using different paths to indicate the result of choosing different production methods to manufacture components.

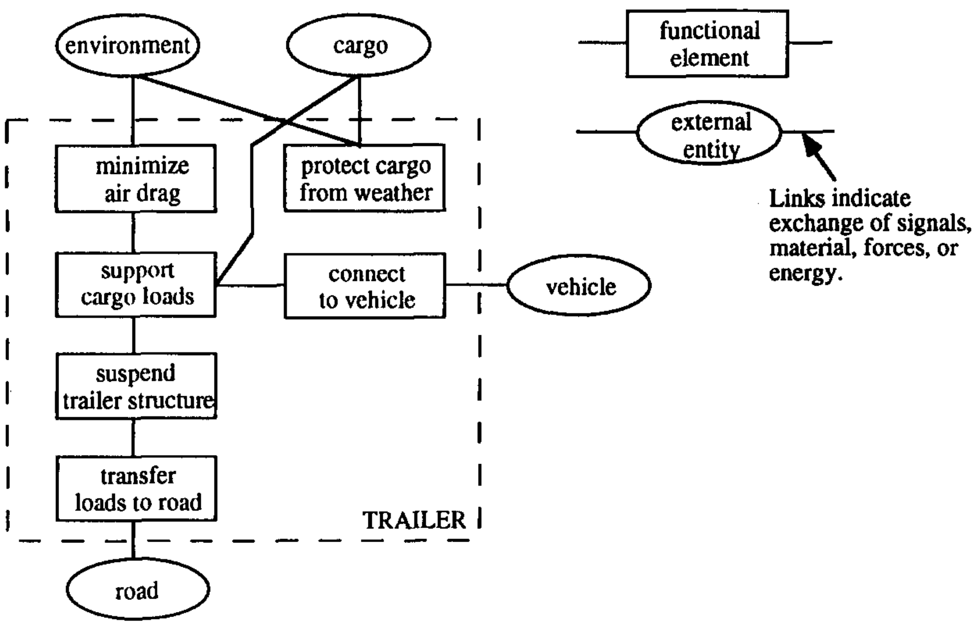


Figure 13: The function structure of a trailer (Ulrich, 1995).

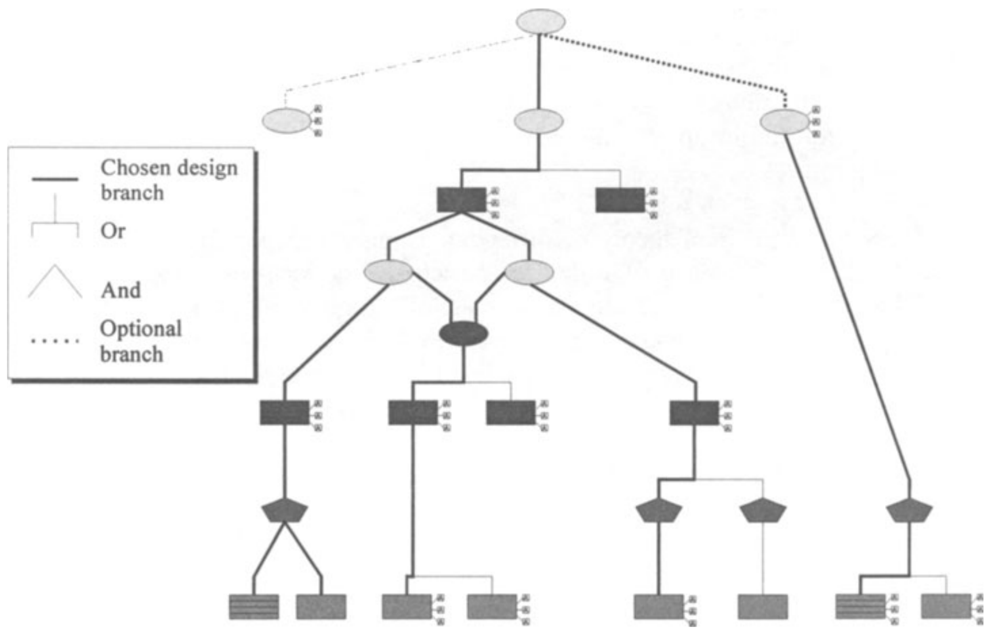


Figure 14: The product configuration structure (Begelinger et al., 1999). Icons: (Optional) Functions = light oval, Means = dark rectangle, Production method = pentagon, (Alternative / combined) Component = light rectangle, connection = dark oval.

The relationship of parts is described by Ulrich (1995) with the term 'interface coupling': *"Two components are coupled if a change made to one component requires a change to the other component in order for the overall product to work correctly".* This can be geometric, as portrayed in Figure 15, or be related to other part requirements that are not considered, such as 'heat resistance'.

Parts that have geometrically coupled interfaces can be coupled with various fits. Manivannan et al. (1989) define three types of fits between geometrically coupled parts: a clearance, interference and transition fit (visualised in Figure 16), each with their own tolerances. To aid designers, software for designing the different fit types exists (Poanta et al., 2008). These three types of fits can be applied to keep parts static or allow them to move within the product, for example in a mechanism. Parts that are locked together tightly due to their geometry have an interference fit. Parts that are free to move relative to each other have a clearance fit. A transition fit can result in both locked and free moving relationships.

To provide information on what influences a part's geometry and in what way, various aspects of the literature above are combined into the geometry-based part coupling approach. The newly created approach should indicate all information types from Table 11.

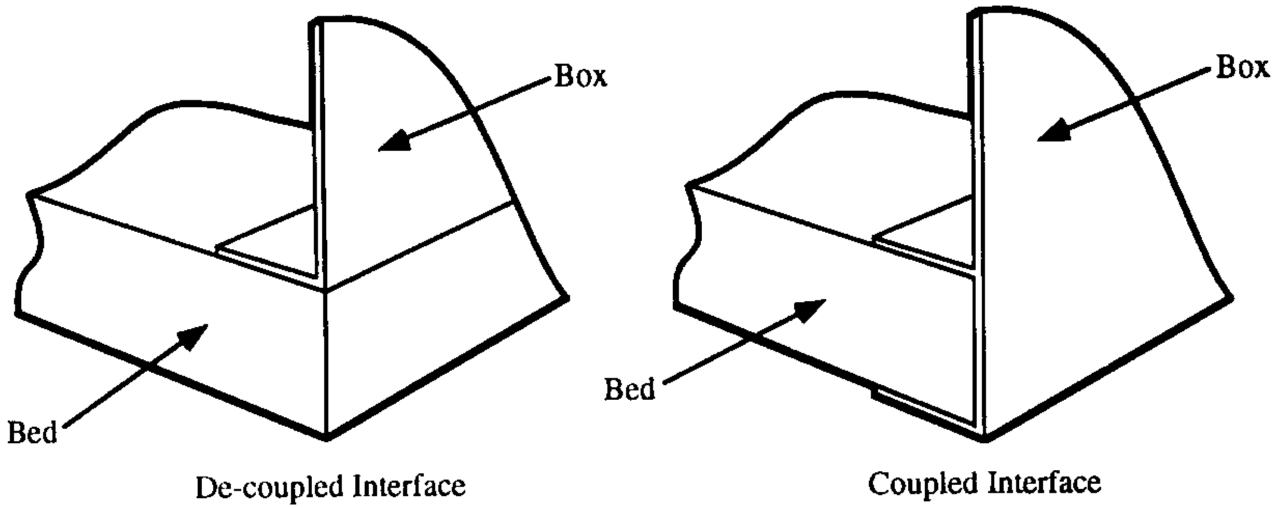


Figure 15: De-coupled vs. coupled interfaces visualised (Ulrich, 1995).

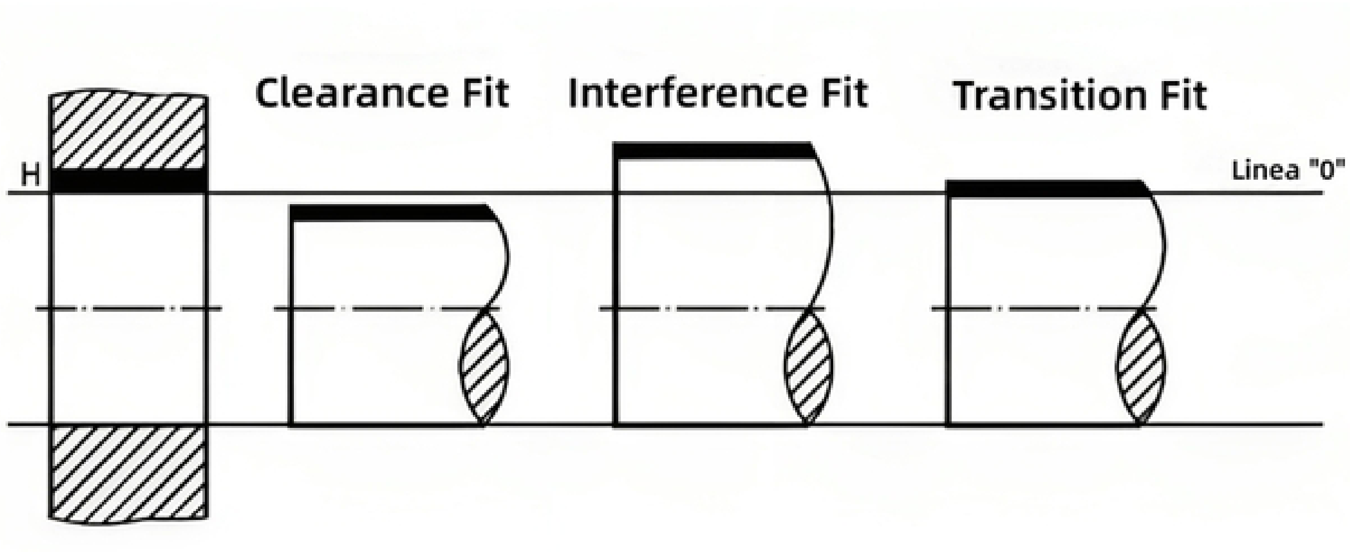


Figure 16: Clearance, interference and transition fits visualised (AT-Machining, 2023).

Table 11: All information types that the geometry-based part coupling approach should indicate.

Information type	Elaboration
All parts present in the product	If some parts are not included in the approach, not all parts that influence a part's geometry may be noted. That would leave gaps in the knowledge why a part's geometry is the way it is, which is undesired.
The manufacturing method with which the part is manufactured	The research is scoped to designing spare parts for IM parts. There should thus be an indication that distinguishes IM parts from parts manufactured with other technologies, to know which parts need to be considered. Furthermore, as shown by Begelinger et al. (1999), using different manufacturing technologies can result in different product configurations and thus different parts that influence a part's geometry.
Which part is coupled to which part	This is required to know which parts influence a part's geometry and which parts do not. This is described by the term 'interface coupling' by Ulrich (1995).
The function that a (group of) part(s) has	A part's geometry is not only shaped for coupling with other components, but also to perform a certain function. This function thus influences the geometry and requirements of the part, which is why it should be indicated in the approach.
The priority that one part's geometry may have over the other	This determines how much design freedom there is to change the geometry of a part. A neighbouring component may have geometry that cannot be changed, for example because it is off-the-shelf and not custom made. Because the coupled parts need to fit around the given geometry of the off-the-shelf component, the off-the-shelf part's geometry may have priority over the parts that are coupled to it. Therefore, the geometric design space is reduced, which is why the approach should indicate this.
The type of coupling between components	The type of coupling depends on whether the two coupled parts move within the product or not. Their behaviour in the product determines how a part fits together with other parts and the tolerances that determine the geometry (Manivannan et al., 1989). This information must be included because the type of fit influences the functionality of the part. For example, if a shaft is supposed to be able to displace within a hole, it needs a clearance fit with the hole. If a spare shaft does not have a clearance fit with the hole, it does not fit and the part is not functionally equivalent with the original shaft.
Other factors that influence the geometry of the part	This includes aspects such as human interaction and electrical connections. Parts that come in contact with the user can for example have ergonomics requirements that determine the geometry of a part. If the part is connected electrically to other components, the geometry of the part must also allow for this, therefore the geometry is influenced.

An additional desire was to base the structure of the product architecture map that was formed with the geometry-based part coupling approach on the disassembly map by De Fazio et al. (2021) (Figure 17). The disassembly map is a product architecture map that displays the components of a product in a map to assess the ease of disassembly. It is an established method in the workflow of designers. Building upon an established method is desired because it enhances the ease of integrating the approach in the existing, intuitive workflow of designers, with the goal of more products that allow for interchangeable, functionally equivalent spare parts manufactured with SLA in the future.

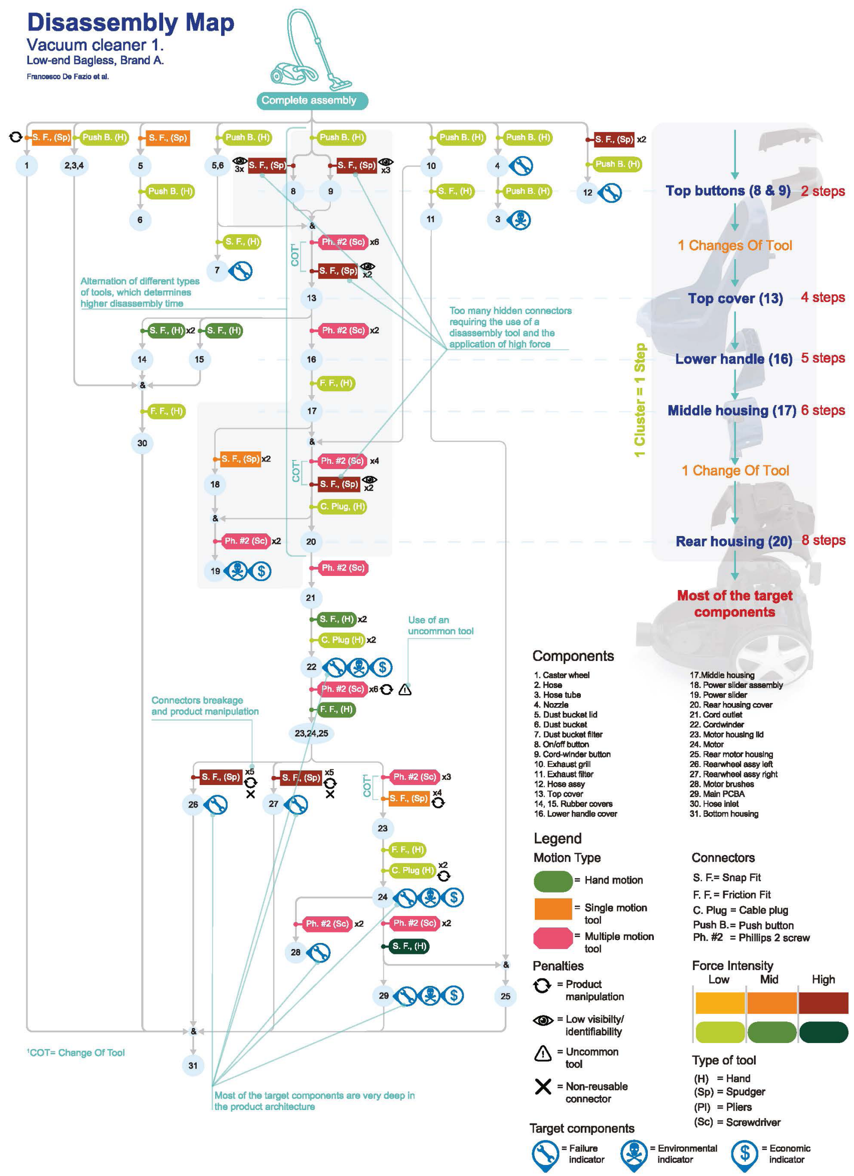


Figure 17: The Disassembly Map method (De Fazio et al., 2021).

4.1.2 | Method for the development of the geometry-based part coupling approach

A Ferm cordless drill was chosen (Figure 18) to develop the geometry-based part coupling approach with. This product was chosen because it is a consumer electronics product that contains plastic IM parts that are used mechanically. Furthermore, the product was chosen because it provided adequate complexity (not too simple, not too complex) to make a product architecture map for.

The drill was disassembled while recording video footage (Appendix C). The drill was disassembled to be able to analyse each part individually, including the parts that are not visible to the user during regular use. Video footage was recorded to be able to trace back the disassembly steps that were

Figure 18: The Ferm cordless drill (CDM1159).

required, as well as to know which part goes where in the product.

A geometry analysis was performed for each part of the drill. This geometry analysis was performed to collect all the information types that are listed in Table 11. The geometry analysis was performed by answering the following list of questions for each part:

1. Is it a custom IM part?

Question 1 was used to determine whether the part should be considered for spare part production with SLA or not. The part needs to be manufactured with IM to be considered for SLA spare part production. The part needs to be custom in order to have design freedom in the OEM design process. If the part was not custom and made with IM, the following options remained:

- Custom, but not manufactured using an IM machine for plastic parts.
- Not custom. These parts were either defined as off-the-shelf, regardless of manufacturing technology, or considered external entities if they are not part of the product. Ulrich's function structure method (1995) also distinguishes between functional elements and external entities (Figure 13).

To provide more insight on the reason why the part is included in the product, the next question that was asked is:

2. What is the function of this part?

Afterwards, the features of the part were analysed, using the recorded video footage for reference. For each feature of each part, the following question was asked:

3. What is the purpose of this feature?

If changing the geometry of a part's feature (for example diameter of a hole) resulted in having to change another part's geometry as well (for example the diameter of a shaft), these parts are considered coupled. Ulrich (1995) describes this coupling of parts as 'interface coupling'. In case of interface coupling, the following questions were asked:

- Is there any form of geometric priority between the coupled parts because the geometry of one of the parts is fixed, for example in the case of off-the-shelf components?
- Which type of coupled interface from Table 12 exists between the two coupled parts, based on their (lack of) movement in the product?

Table 12: Three types of coupled interface types were defined: static, relative displacement and mechanism.

Coupled interface type	Elaboration
Static	This contains two options: • The two parts do not move within the product. • Both parts move identically.
Relative displacement	Movement in one of the parts can occur without moving the other part.
Mechanism	Movement in one part causes a non-identical movement in the other part.

Lastly, some context-related questions were asked to provide additional information on the geometry of the part:

4. Does the part come in contact with humans?
5. Does the part come in contact with electricity?

A disassembly map was composed using the method by De Fazio et al. (2021). In a new map, using the exact same placement of the parts as the disassembly map, the information of the geometry analysis for each part was mapped in a product architecture map using graphic representations. This plotting of geometry information is the geometry-based part coupling approach. The graphic representations are explained in section 4.1.3.

4.1.3 | Results of the development of the geometry-based part coupling approach

This section presents the geometry-based part coupling approach. Figure 19 shows the Ferm cordless drill with the right housing removed to show more components. Figure 20 shows the feature geometry analysis that was performed for the left housing of the Ferm cordless drill. As can be seen in the figure, the result is quite cluttered and it is hard to grasp the purpose of each feature without an overview of the entire product, showing the purpose of the geometry-based part coupling approach.

The disassembly map of the Ferm cordless drill was composed using the Disassembly Map method by De Fazio et al. (2021) (Figure 21). The product architecture map composed with the geometry-based part coupling approach, as shown in Figure 22, builds upon the Disassembly Map method. The geometry-based part coupling approach is an overlay of additional information, specifically regarding the geometric coupling of components. It uses the placement of the parts of the disassembly map as a starting point but leaves out the disassembly action blocks and lines.

All information types listed in Table 11 are included using graphic representations. The legend in Figure 22 explains the meaning of all graphic representations of information in the product architecture map. The graphic representations are also explained more elaborately later in this section. The data for each information type was collected via the geometry analysis explained in section 4.1.2. The overlay's purpose is to be able to determine the relationships between the parts of the product. This aids designers in the process of creating interchangeable, functionally equivalent parts with IM and SLA.

The geometry-based part coupling approach was developed through multiple iterations of the product architecture map of the Ferm cordless drill. More of the information types from Table 11 were gradually incorporated in the approach, whilst experimenting with ways to keep the information organised and legible. All iterations of this product architecture map can be found in Appendix E.

Figure 19: The Ferm cordless drill, with the right housing removed to show more components. Note: not all components are visible.

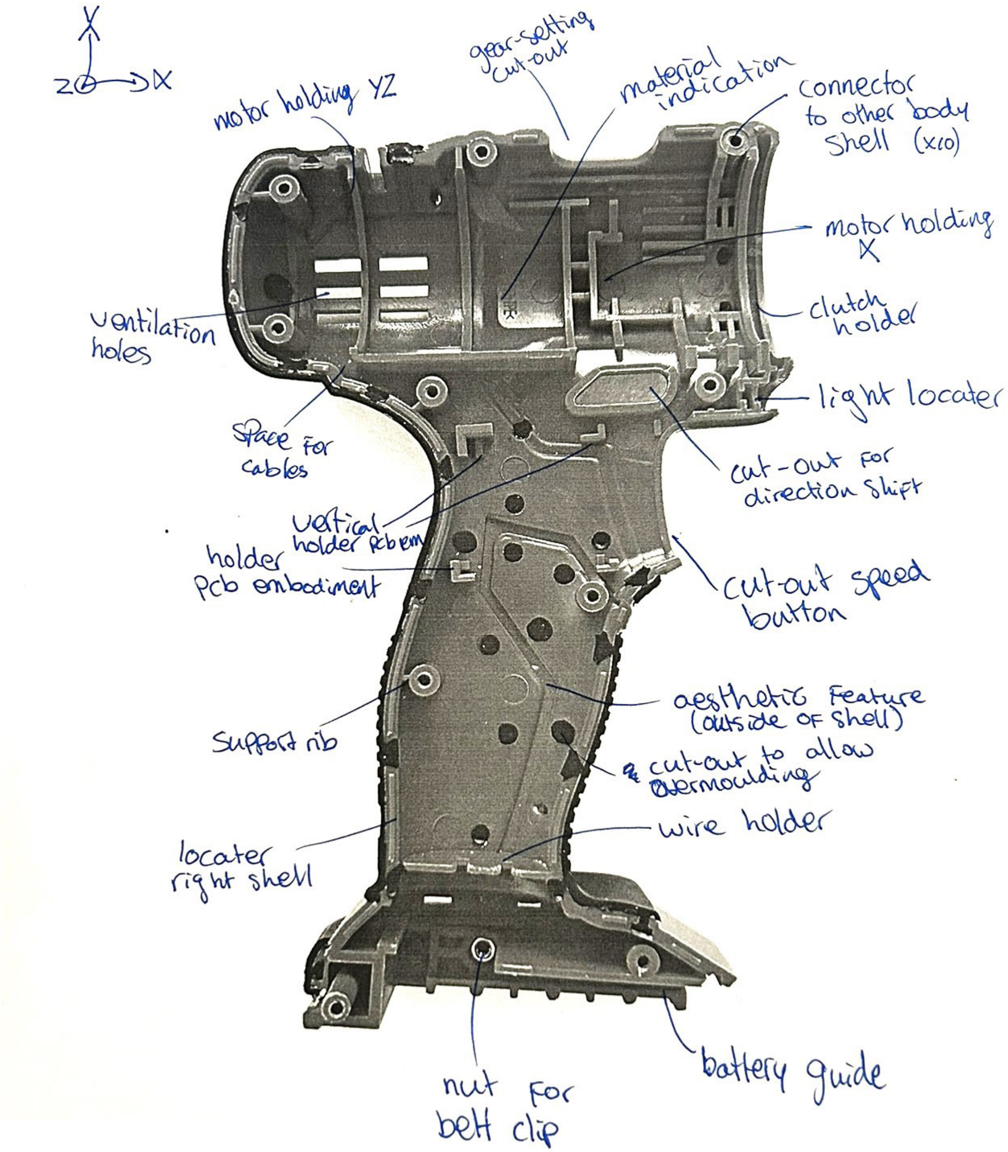


Figure 20: The feature analysis of the left housing of the Ferm cordless drill. Features that appear multiple times with the same purpose were only named once.

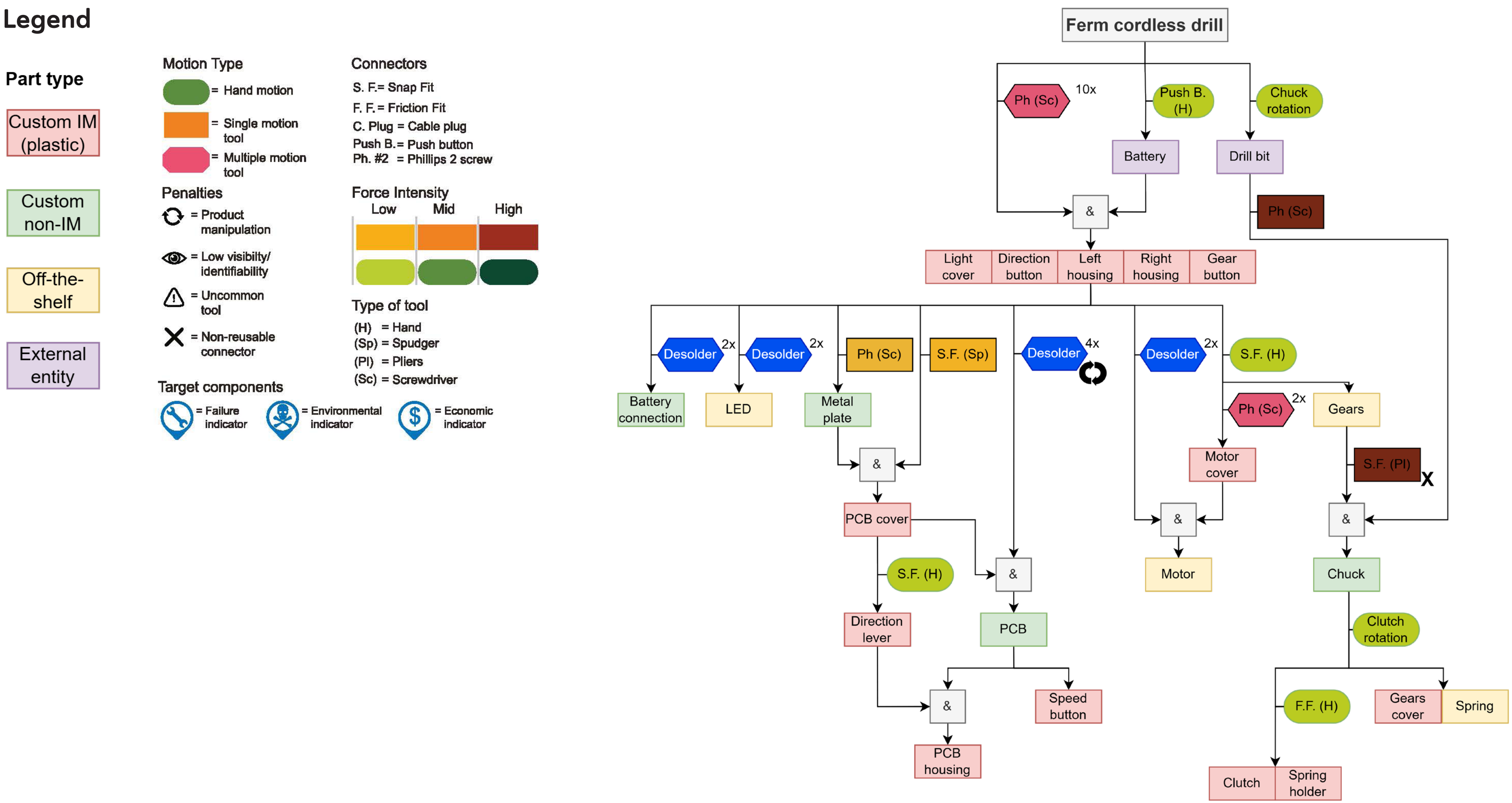


Figure 21: The disassembly map of the Ferm cordless drill, composed with the method by De Fazio et al. (2021). Note: parts were named and colour coded with the geometry-based part coupling approach, whereas the method originally uses numbers in a circle to indicate parts. If multiple parts are revealed by a disassembly step, these are grouped together in the Disassembly Map method. In this disassembly map, each part was named separately. When multiple parts are revealed by a disassembly step, this version of the disassembly map still puts the parts in different boxes (placed adjacently). This change was made so a distinguishment can be made in the geometry-based part coupling approach to indicate more precisely which parts are coupled. Also, the action block 'desolder' is not originally included in the Disassembly Map method but is included here to provide more detailed information on the required disassembly steps.

Legend

Part type

Custom IM (plastic)

Custom non-IM

Off-the-shelf

External entity

Geometry priority

A — B: Part A and B are designed without having priority over one another in geometry and could also have been designed differently.

A → B: Part A's geometry is dominant over part B's geometry. The placement of part A relative to part B is still open.

A ➔ B: Part A's geometry is dominant over part B's geometry. The placement of part A relative to part B is also fixed.

Coupled interface type

Static: Two parts that do not move within the product or two parts that move identically.

Relative displacement: Parts where one part can move without moving the other part.

Mechanism: Parts where movement in one part results in non-identical movement in the other part.

Other

This part comes in contact with the user during regular use.

This part is connected electrically with other parts.

[Function X] These parts perform function X and could be considered a sub assembly.

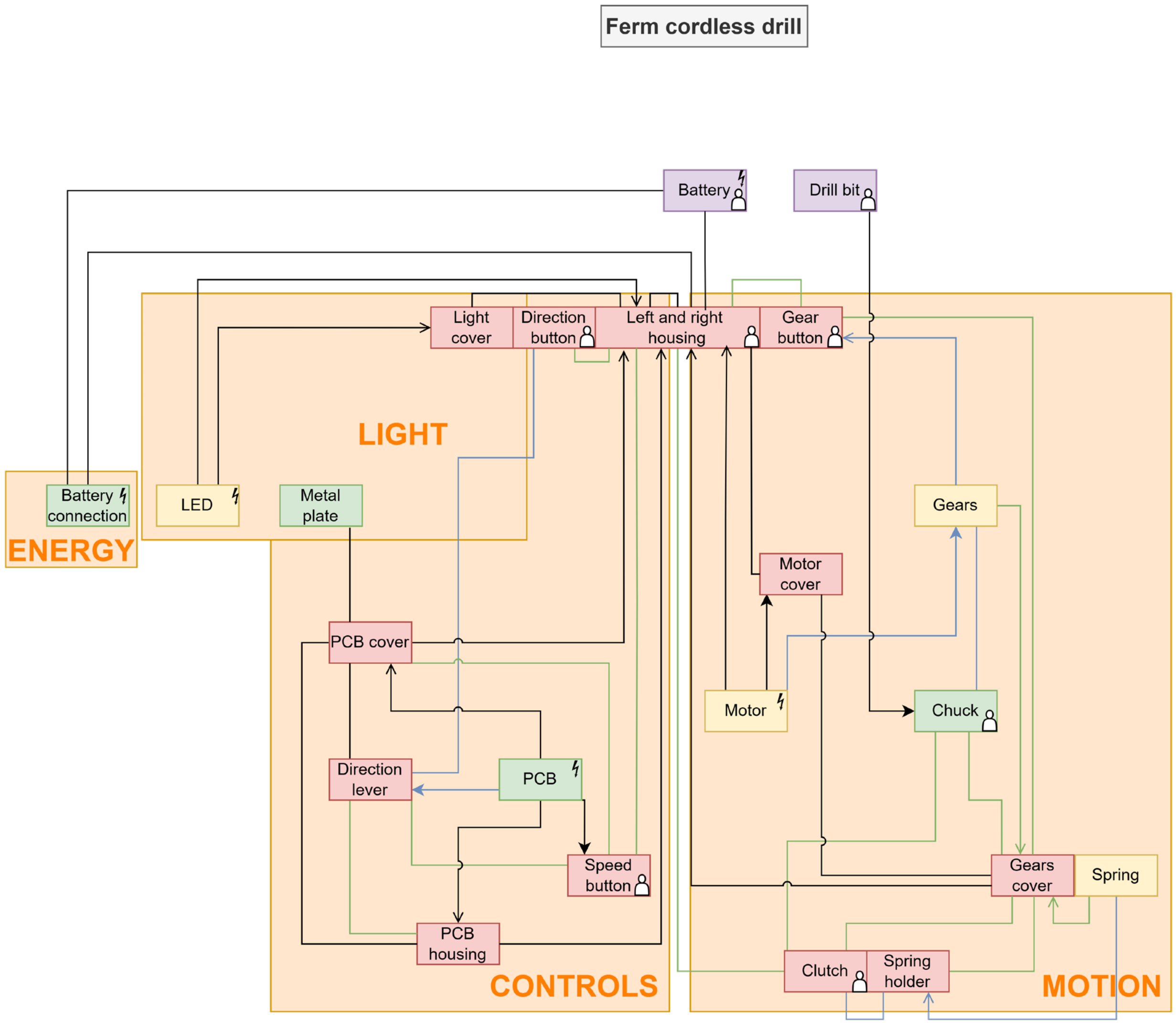


Figure 22: The product architecture map of the Ferm cordless drill, composed using the geometry-based part coupling approach. Note: this product architecture map is made by reverse engineering the OEM product. Some inaccuracies may be present due to lack of access to CAD files and design insights. Some simplifications are also made, such as combining all internal parts of the gearbox into 'gears'. The chuck is also seen as one 'custom non-IM' part, whereas it actually consists of multiple parts that are manufactured with various methods (including IM as well). This was done because the chuck could not be easily disassembled further without permanent damage and the part was not further analysed.

In the small rectangular boxes of Figure 22, all parts of the product are mentioned. The boxes were colour-coded based on their part type, visible in the legend. Distinguishments are made between four part types: custom IM, custom non-IM, off-the-shelf and external entities. For the development of SLA spare parts, only the ‘Custom IM’ parts are considered, graphically represented in red. The rest of the parts are not considered for spare part production. Parts that perform a certain function together were marked within an orange area.

The lines in Figure 22 indicate that the two parts connected with the line share a coupled interface. This means that parts without a line connecting them, do not directly influence each other’s geometry. This is important because if too many parts are considered to influence a part’s geometry, the design freedom could be overly limited, leaving no space to produce an interchangeable, functionally equivalent spare part. An example of coupled parts: the geometry of the gear button is coupled to the gears, the gears cover and the outer housing, but not to any of the other parts of the Ferm cordless drill (Figure 23).

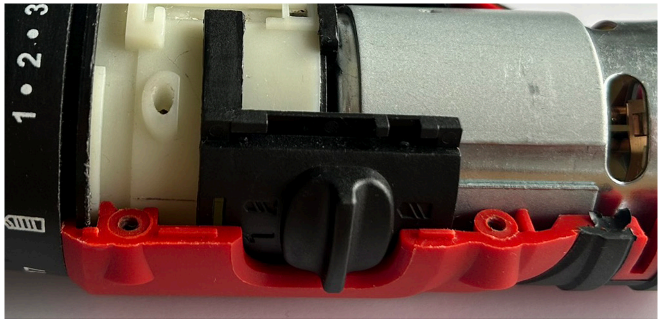


Figure 23: Coupling of the black gear button to the gears (hidden), gears cover and the left and right housing, but not to any other parts.

The arrow types in Figure 22 indicate the geometric priority of one part to the other. Three types were distinguished:

- Lines **without arrowhead** indicate that the parts have no clear priority over one another. This means that both geometries were considered equally important and simply designed to fit together. Some design choices may have even been somewhat arbitrary. An example is the coupling of the printed circuit board (PCB) housing and PCB cover (Figure 24, top).
- When the line has a **thin arrowhead**, part A (located at the origin of the arrow) has priority in its geometry over part B (located at the arrowhead). A thin arrowhead means that that the geometry of part A determines the geometry of part B, but the positioning of part A compared to part B is arbitrary. An example is the placement of the motor within the left and right housing. The motor’s geometry determines the shape of the housing, but the motor could have also been placed elsewhere within the housing (Figure 24, middle).
- With a **thick arrowhead**, part A not only has priority over the geometry of part B, but also on its position relative to part B. An example of this is the placement of the motor cover relative to the motor. It needs to be placed adjacent to the motor and the fastener holes need to be aligned with the tapped holes of the motor (Figure 24, bottom).

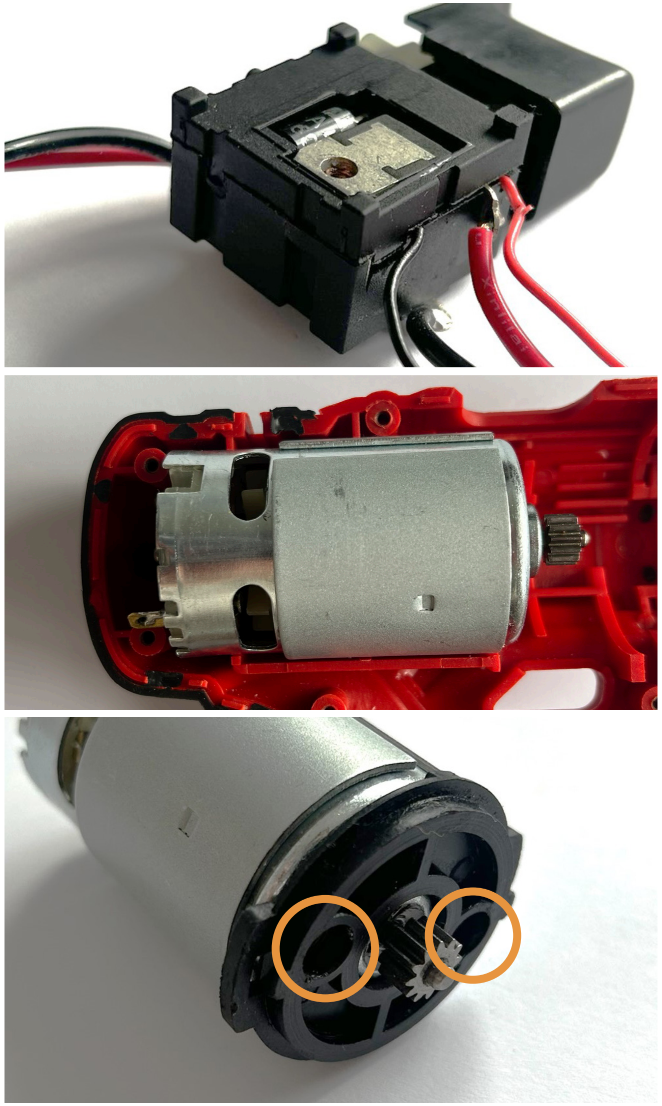


Figure 24: Three examples of priority types. Top: no priority between the PCB housing and PCB cover. Middle: geometric priority of the motor over the left housing. Bottom: geometric and positional priority of the motor over the motor cover.

The colour of the arrows in Figure 22 indicates the coupled interface type between the parts. Distinctions have been made between three types of coupled interfaces:

- **Static:** Two parts that do not move within the product or move identically. The parts can be locked geometrically and/or with a fastener. Fasteners are not included as parts in the product architecture map. Similar to the Disassembly Map method by De Fazio (2021), they are regarded as a connection type and not a part, to keep the map from becoming too cluttered. An example of two statically coupled parts is the battery connection to the left and right housing (Figure 25, top). The battery connection is kept in place in the housing with a transition fit: the part cannot be displaced during regular use, but it is not so tight in the product that it cannot be removed with hand motion during disassembly.
- **Relative displacement:** One part can move without moving the other part. An example of this is the displacement that is possible of the speed button whilst the left and right housing stay stationary (Figure 25, middle). The button has a clearance fit within the housing, meaning that it can move freely within the product.
- **Mechanism:** Displacement of one part within the product causes displacement in the other part. An example of this is the mechanism between the direction button and direction lever (Figure 25, bottom). Moving the black direction button up and down means that the white direction lever is displaced too.

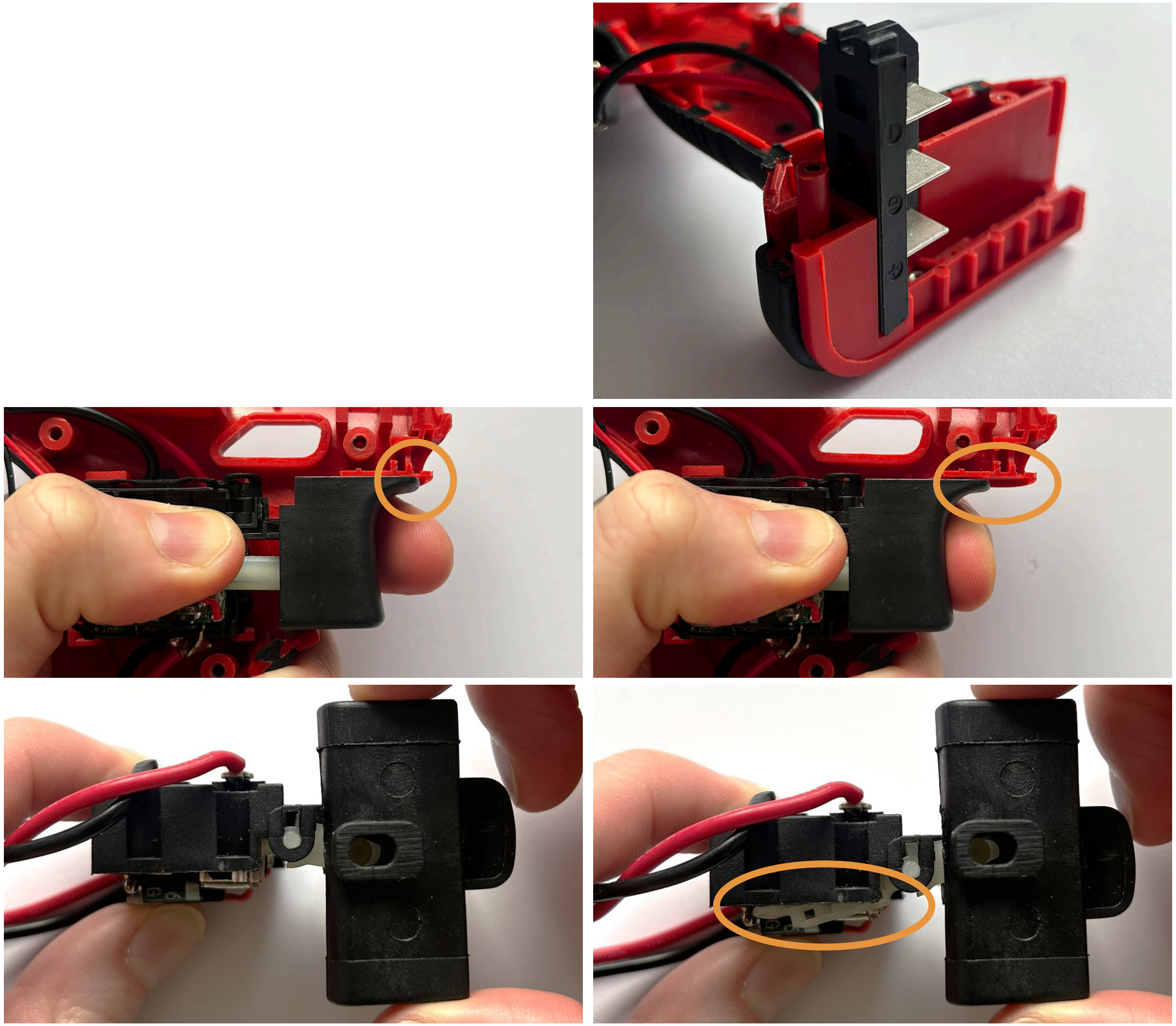


Figure 25: Three examples of coupled interface types. Top: static. Middle: relative displacement. Bottom: mechanism.

Some more context-related information is also portrayed in in Figure 22. A human figure icon indicates that a part comes in contact with the user during regular use. Aspects such as aesthetics and ergonomics may therefore influence the geometry of this part. The thunderbolt icon indicates that the part is electrically connected to other parts. The geometry of the part thus needs to allow for an electrical connection to other parts in the product.

4.1.4 | Conclusion of the development of the geometry-based part coupling approach

The goal of this section was to find a way for designers to know the relationships of parts in a product, as a first step to determining the available geometric design freedom to change a part's geometry. The geometry-based part coupling approach was developed, as an additional layer of information on top of the existing Disassembly Map method by De Fazio et al. (2021). The approach was used to compose a producing architecture map that indicates the type of coupling between the parts of a Ferm cordless drill. The approach uses various graphical representations to indicate:

- all parts present in the product.
- the manufacturing method with which the part is manufactured.
- which part is coupled to which part.
- the priority that one part's geometry may have over the other.
- the function that a (group of) part(s) has.
- the type of coupling between components.
- the context of the part, which includes human interaction and electrical connections.

Now that there is an approach to know the relationships between coupled parts in a product, the next step in the process of designing interchangeable, functionally equivalent parts is understanding what design space is actually left in a product.

4.2 | Form factor definition approach

With the geometry-based part coupling approach developed, there is a way for designers to determine which parts are coupled in a product. The second step in knowing the available design freedom to design interchangeable, functionally equivalent parts is analysing how much space is left by the coupled parts. An approach to determine the available design space is explored in this section.

Section 4.2.1 contains the literature that was consulted to compose the approach. Section 4.2.2 contains method that was used and section 4.2.3 contains the result. Section 4.2.4 contains the conclusion of section 4.2.

4.2.1 | Literature on mapping design space

Tang et al. (2016) use two types of information to describe a physical entity: material information and geometrical information. The geometrical information is split up in two parts: functional volumes and functional surfaces. Functional volumes and surfaces are used to differentiate between design space and non-design space of a physical entity. Functional volumes describe the geometrical volume of the physical entity, whereas functional surfaces describe the key surfaces of the entity required for its function.

An example of a triple clamp (Figure 26) is given to illustrate how the functional volumes and functional surfaces of a part are defined (Figure 27). The functional surfaces ensure the right functionality of the triple clamp. Five functional surfaces are defined that the clamp has to attach to: two for the front fork, one for the frame and two for the steering handle. The functional surfaces in this case represent the coupled interfaces of the triple clamp to its three coupled parts. These five functional surfaces are the non-design space: there is no choice but to have surfaces of the part there. Around the non-design space, functional volumes are set up that define the design space that the part's geometry must fit within. In this case, the design space was dimensioned to the outer dimensions of the original part.

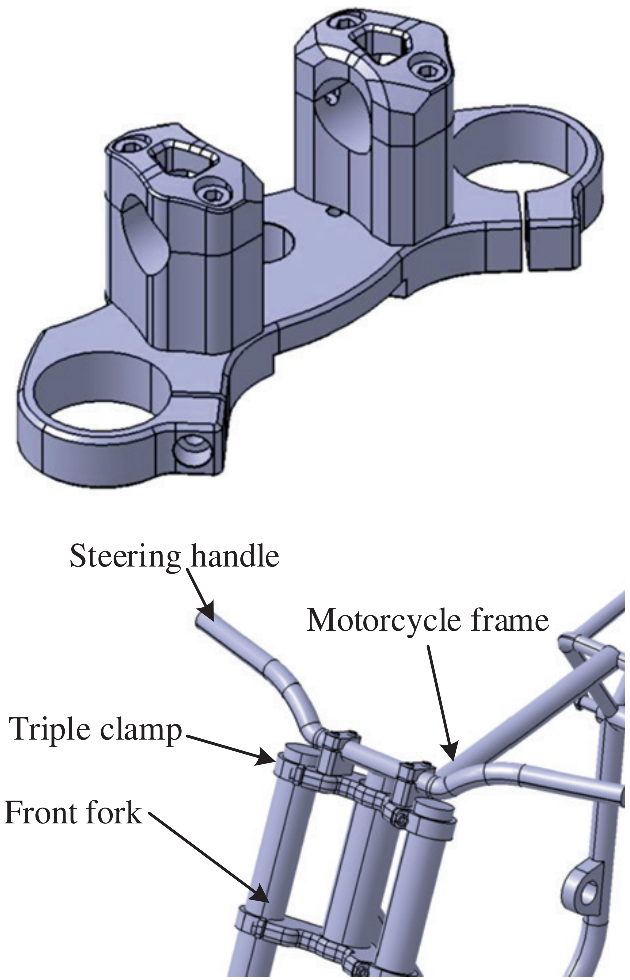


Figure 26: The triple clamp that is used as an example to illustrate the design space and non-design space (Tang et al., 2016).

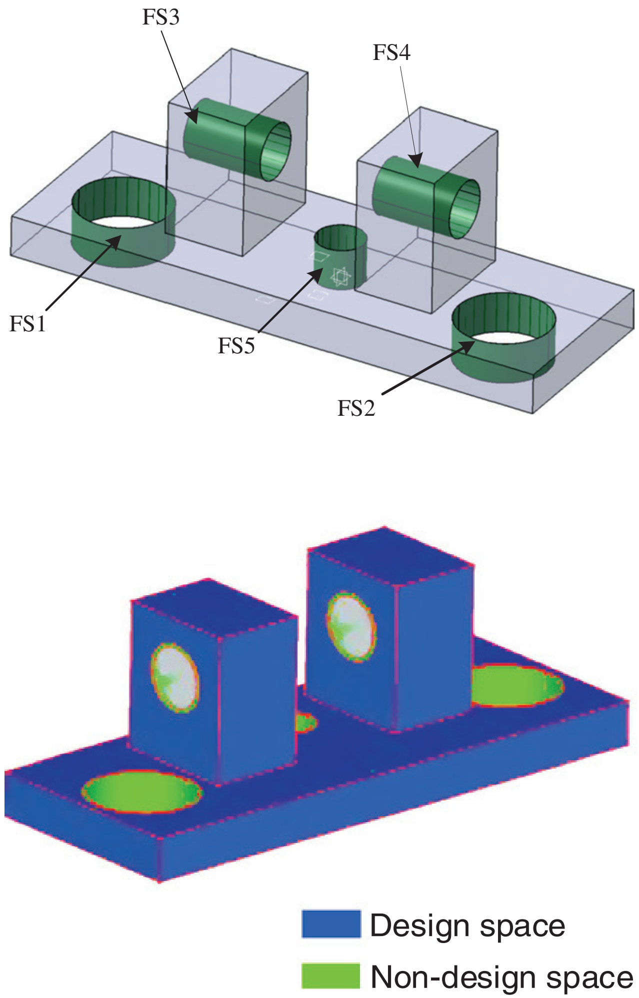


Figure 27: With functional volumes and functional surfaces (FS1 through FS5), the design space and non-design space can be indicated (Tang et al., 2016).

The functional surfaces of a part do not always only consist of the coupled interfaces of a part. Figure 28 shows an example of an air foil, where the outside surface is a functional surface to ensure the right airflow. This functionality is defined through the part requirements.

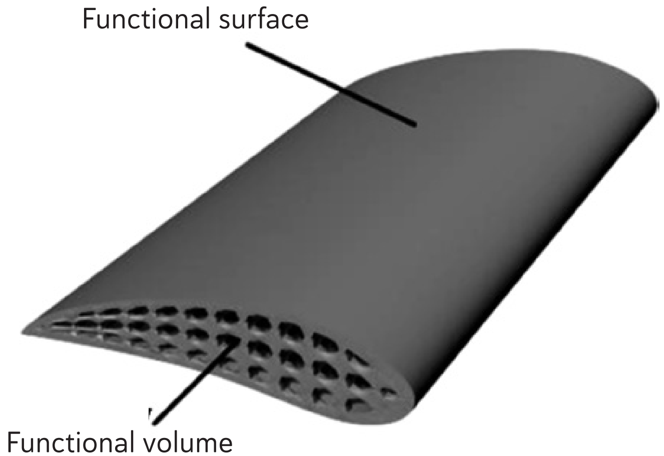


Figure 28: The functional surface and functional volume of an air foil (Tang et al., 2016).

Functional surfaces and functional volumes can be described geometrically by parameters. These parameters are also referred to as 'Design Degrees of Freedom' by Tang et al. (2016). An example of a cylinder is shown in Figure 29. Four Design Degrees of Freedom define a cylinder: the length, the diameter, the centre point and axial direction.

It may occur that a part's geometry is defined by another part. In the geometry-based part coupling approach, this was indicated with the arrow graphics (Figure 22). When this occurs, one or more of its parameters are fixed and the number of Design Degrees of Freedom is decreased by the number of fixed parameters. For example, if the cylinder from Figure 29 is supposed to fit with an interference fit in a defined through-hole, the axial direction and diameter are fixed. The cylinder thus has only two Design Degrees of Freedom: the length and centre point.

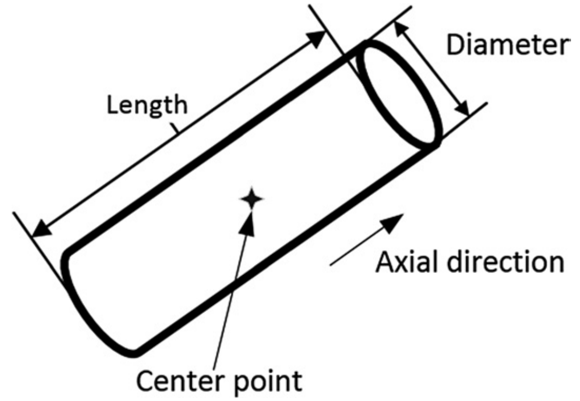


Figure 29: A cylinder's geometry and position can be fully defined with four parameters (Tang et al., 2016).

4.2.2 | Method for the development of the form factor definition approach

The information about a part's design space and non-design space, defined by the parameter-based method by Tang et al. (2016), is referred to as the 'form factor' of a part. The form factor of the part thus contains the information regarding the geometry of a part that is required to produce an interchangeable, functionally equivalent part. The approach of defining the design space and non-design space parametrically with functional volumes and functional surfaces is referred to as the 'form factor definition approach'.

The form factor definition approach was applied to a case study to assess how it can be used to design an interchangeable, functionally equivalent spare part. The product chosen for the case study is the Bosch hand blender (Figure 30) because it is a consumer electronics product with IM parts that engage in mechanical systems. The chosen part is the speed button (Figure 31). It was chosen because:

- it is an IM part involved in one of the mechanisms of the part.
- it is a relatively simple part that provides a good starting point to apply the approach to.
- it is a part that requires a spare part, because the part was already broken when it was collected to use in this case study.

Figure 30: The Bosch hand blender ErgoMixx Style (Bosch, 2025).

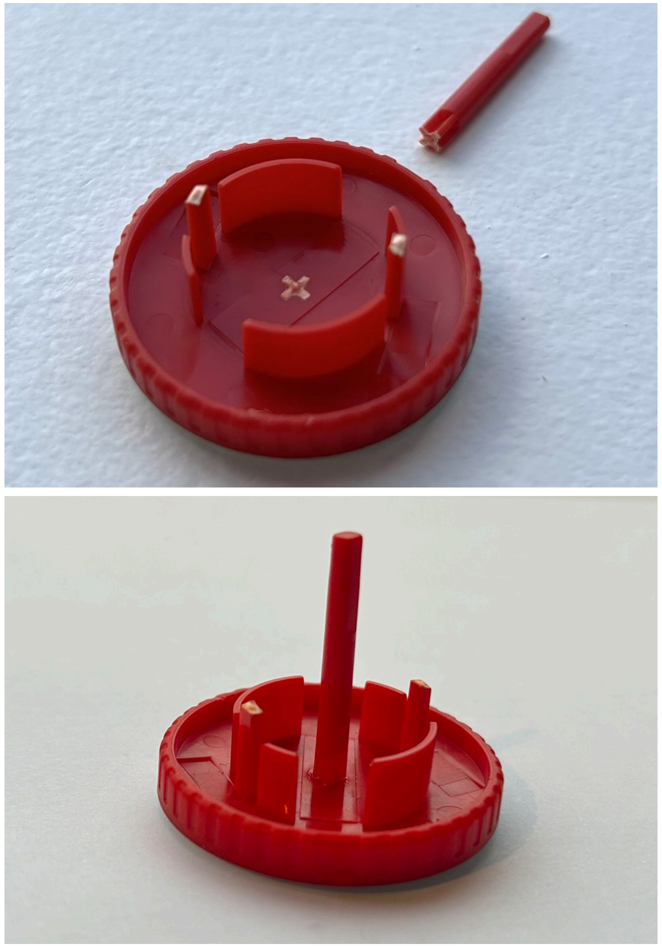


Figure 31: The speed button of the Bosch hand blender. The shaft was broken before collection to use in the case study and temporarily repaired.

The Bosch hand blender was first disassembled while recording video footage, to be able to look back on which part belongs where in the product. Then, a product architecture map was made, using the geometry-based part coupling approach from section 4.1. This was done to understand the relationships that the speed button has to the other parts in the product. Only the parts coupled to the speed button are shown in Figure 32. The coupled parts of the speed button are assumed to be fixed in geometry. Therefore, the coupled parts determine both the functional surfaces that the speed button needs to have (the non-design space) and the available space to work within (design space).

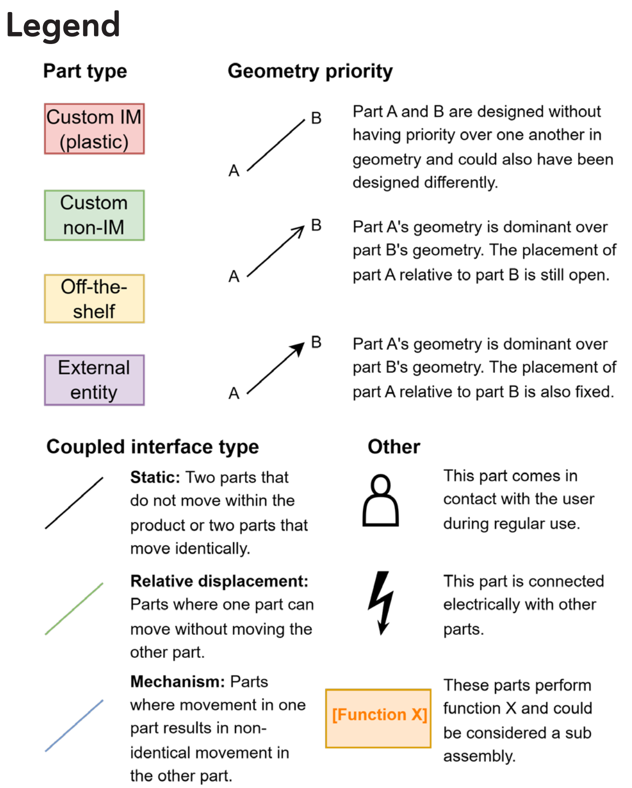
The geometry of the parts coupled to the speed button were analysed to define the non-design space with functional surfaces. These functional surfaces are where the coupled interfaces of the parts are situated. Then, the available design space that the part must be designed within was determined by inspecting the parts visually. The design space and non-design space were mapped in an overlay over a picture of the original speed button. The non-design spaces were also indicated in the product architecture map, to provide additional information on the coupling of the parts.

Lastly, the available design space for the speed button was modelled in the SolidWorks CAD 2023 software. The model was later annotated to indicate the non-design spaces. The digital 3D model of the available design space was used to manufacture an interchangeable, functionally equivalent spare part of the speed button of the Bosch hand blender.

4.2.3 | Results of the development of the form factor definition approach

The product architecture map of the speed button and its coupled parts is shown in Figure 32. The parts coupled to the speed button are the PCB and the front housing (Figure 33). The product architecture map indicates about the speed button that:

- it is a custom IM part, indicated by the red rectangle.
- it belongs to a group of parts with a 'controls' function, indicated by the orange area.
- its geometry is coupled with a 'mechanism' coupled interface type to the PCB, indicated by the blue line colour. Furthermore, the PCB's geometry determines the shape and placement of the feature that connects to the PCB, indicated by the solid arrowhead.
- its geometry is coupled with a 'relative displacement' coupled interface type to the front housing, indicated by the green line colour. There is no priority in geometry, indicated by the lack of an arrowhead.
- it is a part that the user comes in contact with, indicated with the human figure icon.



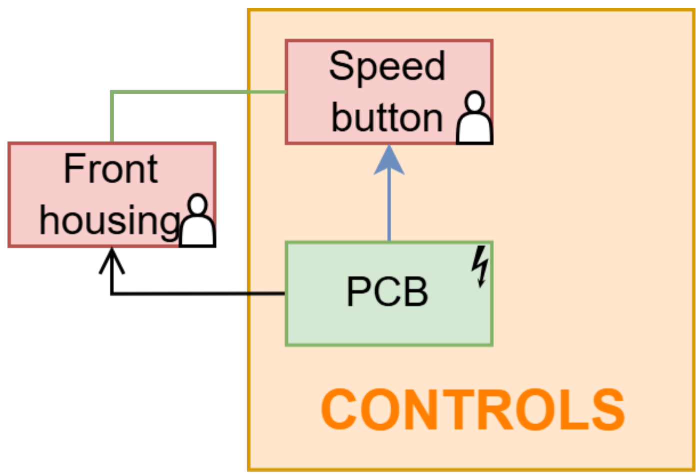


Figure 32: A partial product architecture map of the Bosch hand blender, containing the parts that share coupled interfaces with the speed button.

The design space and non-design space of the speed button of the Bosch hand blender are shown in Figure 34 in 2D. The design-space of the speed button is determined by the available space that is left in the product by the front housing and PCB. Four functional surfaces define the non-design space, listed below:

a. The outer diameter of the speed button has a clearance fit with the same concentric surface in the front housing. This outer diameter allows the user to turn the button to the desired setting. The bottom surface around the outer diameter makes sure that the button sits at the right depth in the housing (Figure 35, left).
b. The outer diameter and bottom surface of the guide tab further ensure that the speed button sits concentrically and at the right depth within the housing and the button does not rack around (Figure 35, left). The fit is a transition fit.
c. A hook allows the speed button to be inserted in a keyway in the front housing and ensures the button does not fall out the housing (Figure 35, right).
d. The shaft diameter, combined with a flat surface on the shaft, allow the speed button to turn the potentiometer located on the PCB (Figure 36). The fit is a transition fit.

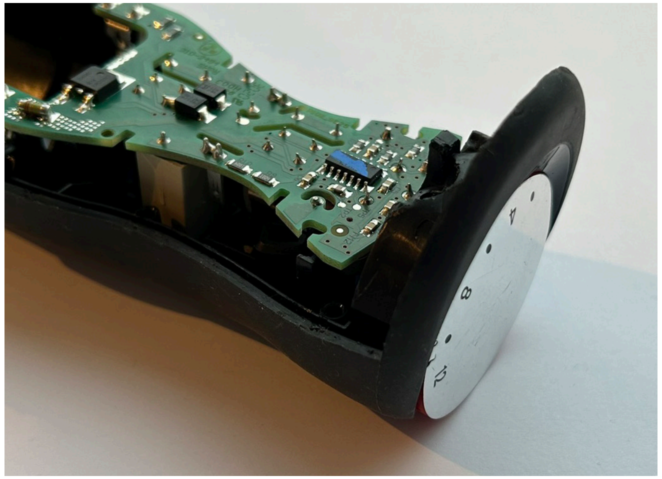


Figure 33: The speed button, the front housing and the PCB.

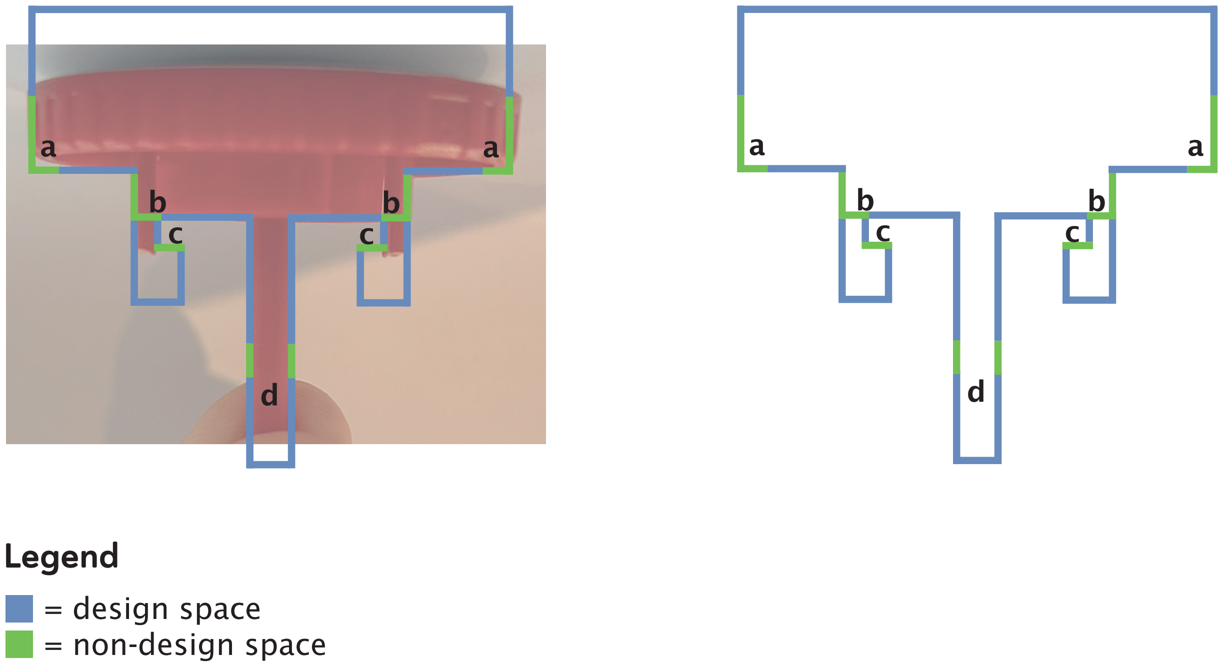


Figure 34 : The design space and non-design space for the speed button of the Bosch hand blender in 2D, with (left) and without (right) underlay of the original part. Note: in theory, the geometrical design space upwards from surface a is in in fact geometrically infinite, because there are no features blocking the design space. However, it assumed that the design space is cut off just above functional surface a. This also makes sense for user ergonomics, aesthetics and limiting material usage.

An exploration was performed to see if a part's non-design space could also be fully defined in parameters. For example, simply indicating the axis of rotation of a button, but not the exact dimensions of the features. However, this turned out to be very chaotic and did not fit in the workflow of a designer, thus the approach was not further explored. The exploration is shown in Appendix F.

Figure 35: The front housing and speed button's coupled interfaces (a, b, c).

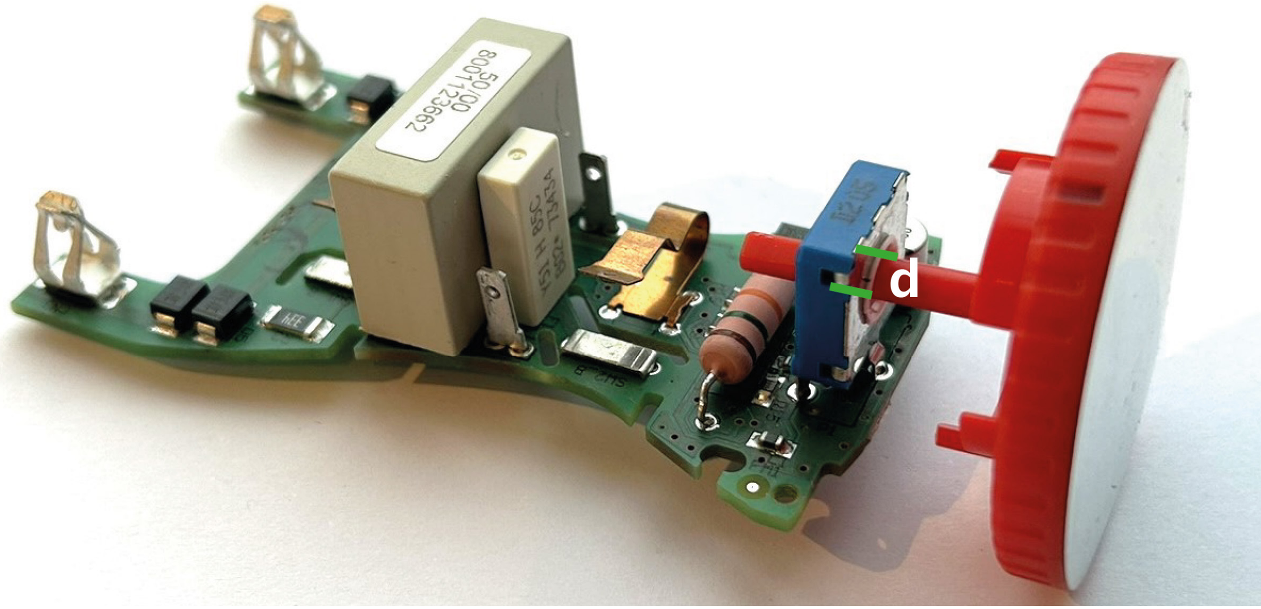


Figure 36: The PCB and speed button's coupled interface (d).

Inserting the functional surfaces in the product architecture map indicates how the coupled interfaces and functional surfaces are related (Figure 37):

- The relative displacement possible between the speed button and front housing is enabled by functional surfaces a, b and c. As explained, functional surface a and b make sure the part sits at the right depth and concentricity, while functional surface c makes sure the button cannot be taken out (Figure 35).
- The mechanism between the PCB and speed button is enabled by functional surface d. As explained, the diameter and flat surface of the shaft allow the turning of the speed button to be translated into a cascading turning of the potentiometer on the PCB. The dimensions and placement of the potentiometer on the PCB determine the geometry and position of the speed button (Figure 36).

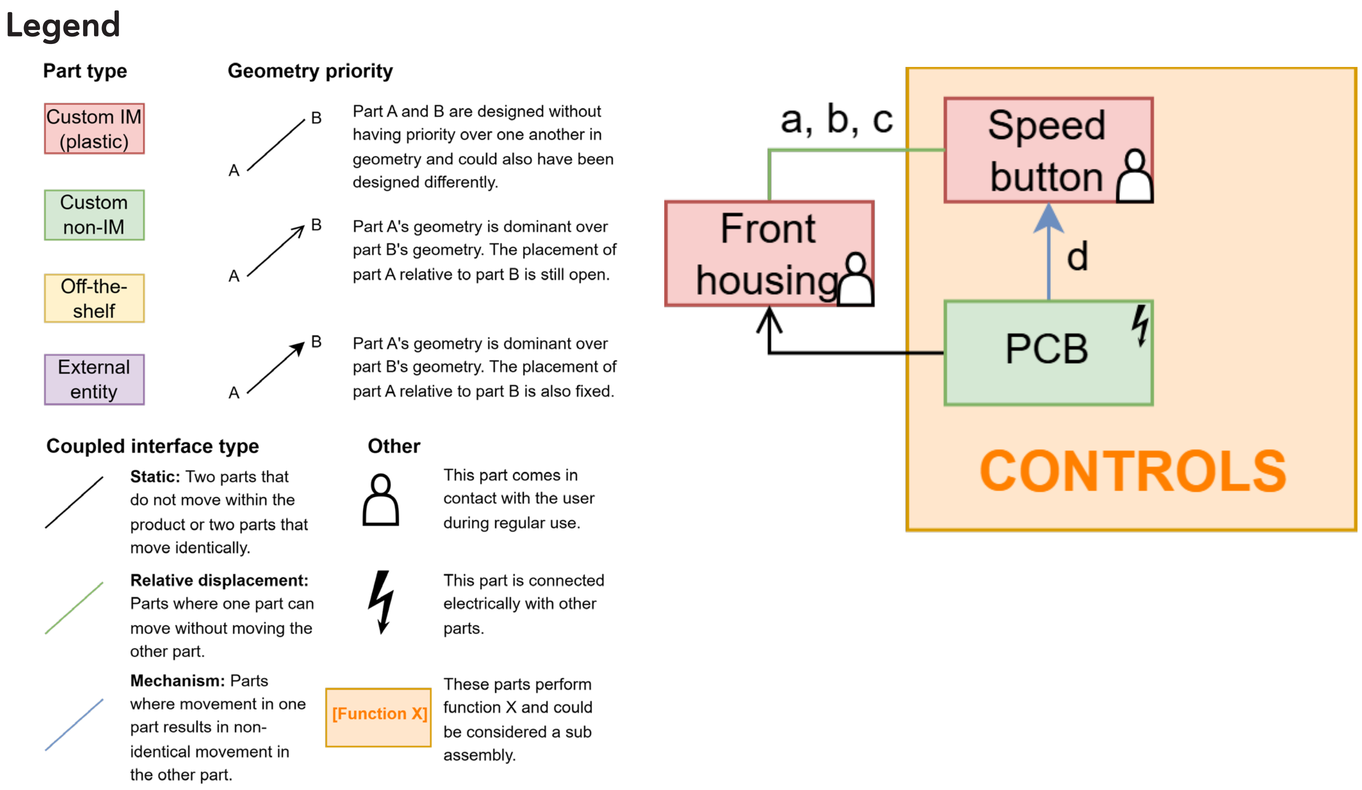


Figure 37: The functional surfaces of the speed button of the Bosch hand blender indicated in its product architecture map.

With the design space and non-design spaces drawn in 2D, the design space was modelled in SolidWorks 2023 CAD software. This is where the Design Degrees of Freedom of the features were used. The Design Degrees of Freedom of the features were used to define the model's dimensions and geometry. Two ways of modelling the design space were tried:

- **Subtractive:** The features of the PCB and front housing that influenced the design space of the speed button were modelled (Figure 38). A cylindrical bounding box of the speed button was modelled too, dimensioned to the largest width and height of the design space (Figure 39). Subtracting the models of the PCB and front housing from the cylindrical bounding box of the speed button results in the model portrayed in Figure 40. The next step was to remove any bodies that were not removed but also not part of the design space.
- **Additive:** Modelling the design space up to its defined boundaries.

Regardless of the chosen approach, the end result is the same model of the design space (Figure 41).

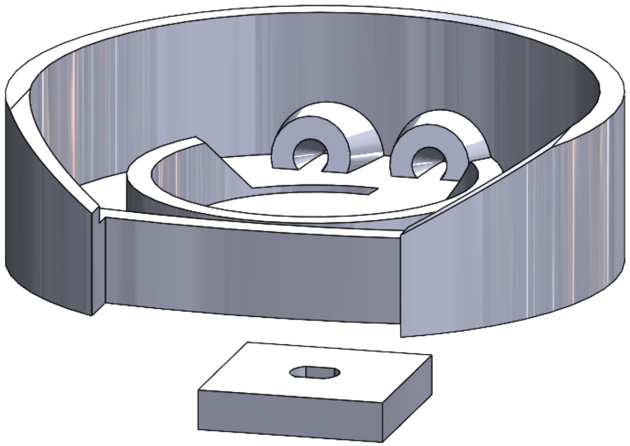


Figure 38: The coupled parts of the speed button modelled in CAD.

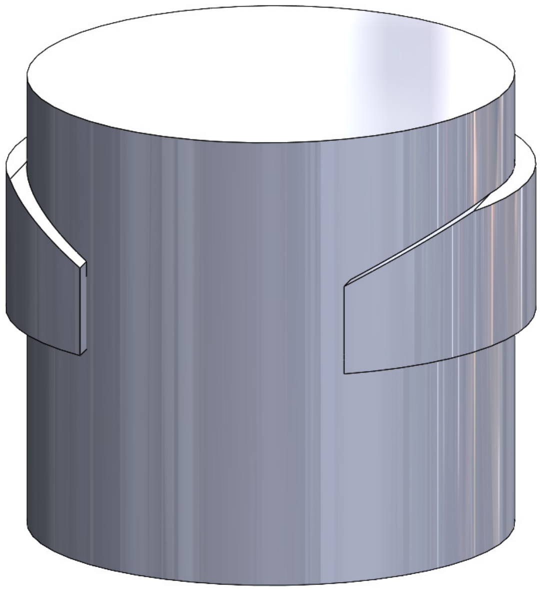


Figure 39 : The bounding box of the speed button modelled around the coupled parts (PCB and front housing).

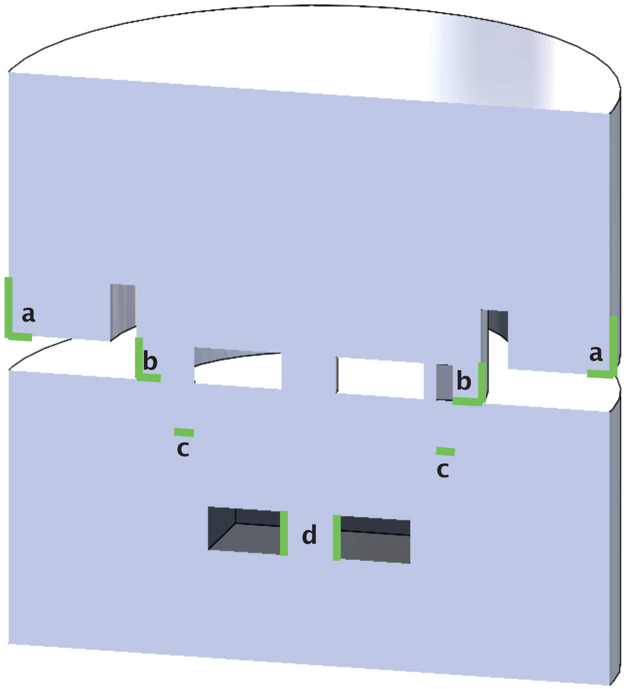
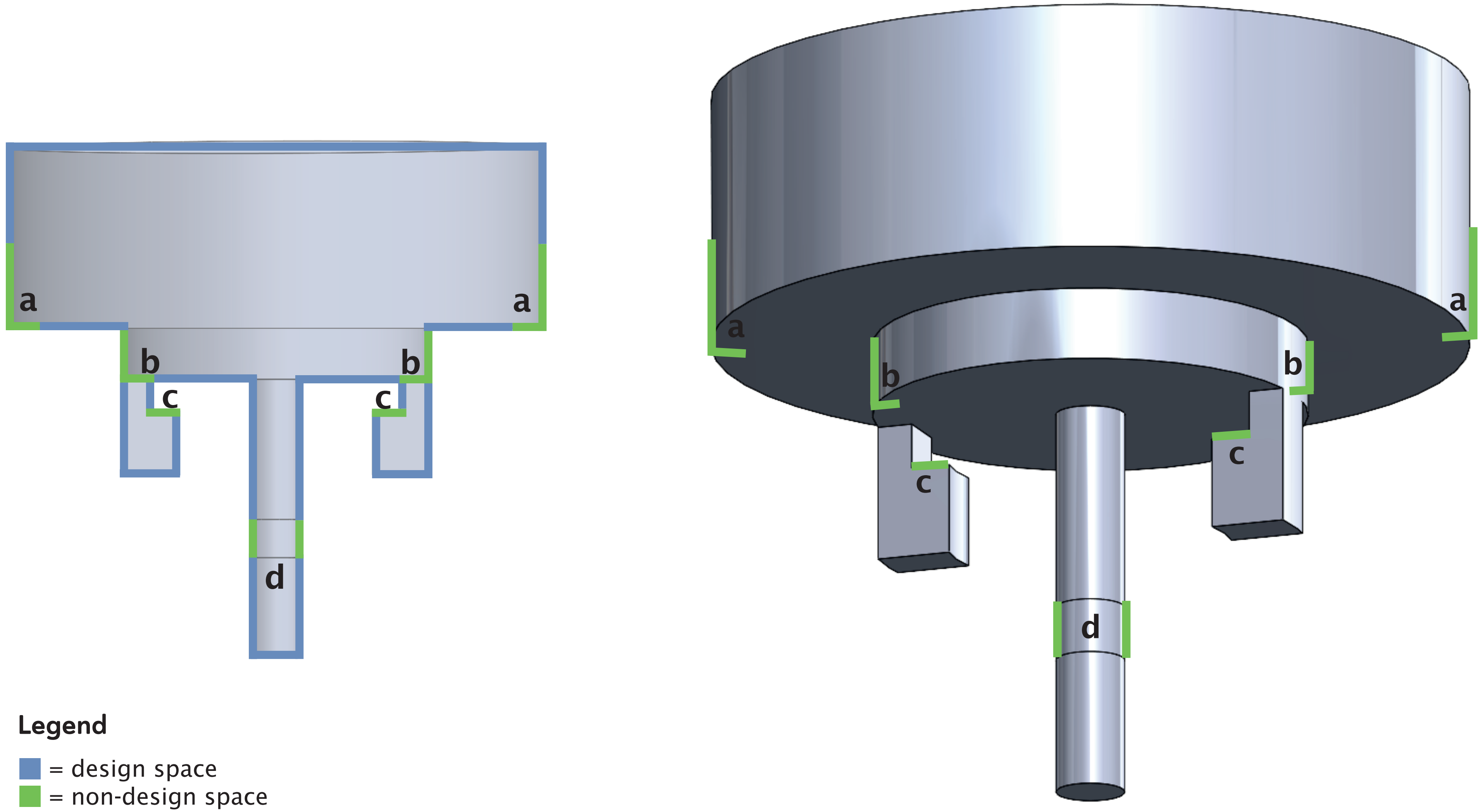


Figure 40 : The bounding box of the speed button minus the coupled parts (PCB and front housing), in an isometric cross section view annotated with functional surfaces a, b, c and d.



Legend

= design space
= non-design space

Figure 41: The available design space of the speed button modelled in CAD, annotated with its required functional surfaces.

To assess if the design-space and non-design space were correctly defined, a prototype of the speed button was made using FDM (Figure 42). FDM was used instead of SLA because an FDM print could be produced quicker at the time. Functional surfaces a, b, c and d are included in the part and indicated in Figure 42. The part also fits within the defined design space.

As shown in Figure 43, the geometry of the original IM part is different than that of the AM spare part. Nevertheless, the AM spare part fits in the product and performs the function that the speed button was made for: turning the potentiometer on the PCB (Figure 44). The form factor definition approach in this case thus successfully defined the available design freedom to end up with interchangeable, functionally equivalent parts with IM and AM.

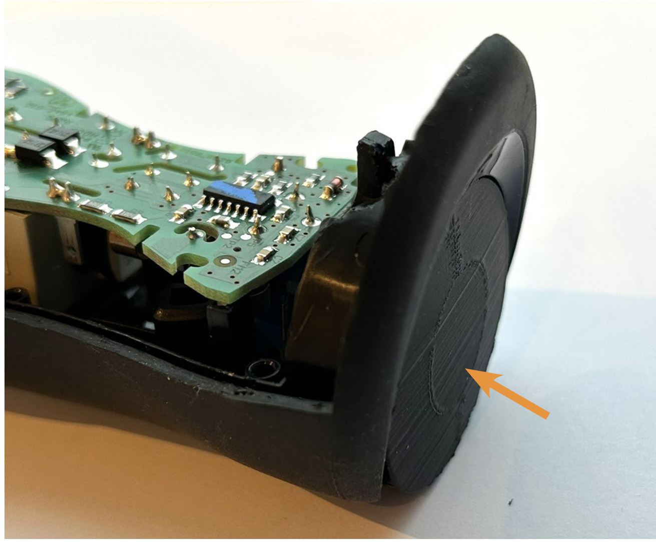


Figure 44: The spare speed button is interchangeable with the original IM part and is functionally equivalent.

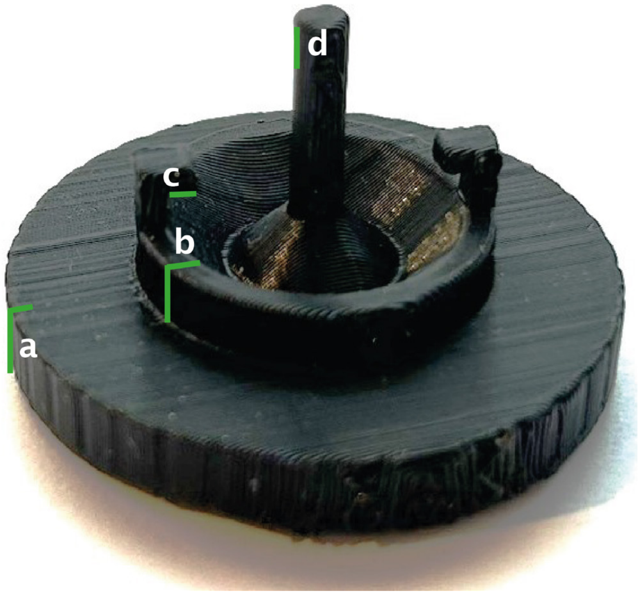


Figure 42: The FDM prototype of the spare speed button, designed within the form factor that was determined using the form factor definition approach, annotated with functional surface a, b, c and d.

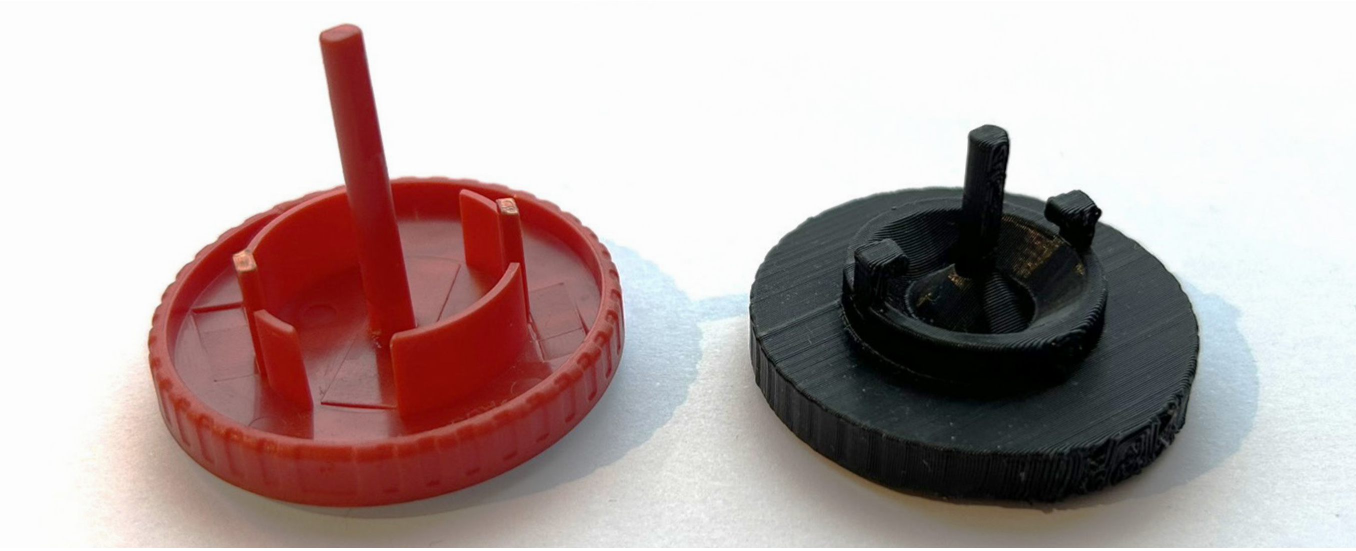


Figure 43: The original IM speed button has different geometry than the AM spare part, but these two parts are interchangeable and functionally equivalent.

The functional equivalence of the original IM part and AM spare part was not only dependent on the integration of the functional surfaces in the part. The geometry of the part that connect the functional surfaces together within the defined design space must also meet the part requirements. For example, the shaft of the speed button that connects functional surface d (in Figure 42) to the rest of the speed button must be able to withstand a certain lateral load. If it is too thin, it may break off during use. This happened to the original IM part, as shown in Figure 31. This would mean that the parts are not functionally equivalent, even though functional surface d was integrated in the design. To prevent this, a chamfer was added to the shaft in the FDM prototype.

Furthermore, Tang et al. (2016) not only used geometrical information to describe a physical entity, but also material information. The material properties of the part also determine how well the part performs. For example, the shaft of the speed button as shown in Figure 31 may not have broken if it were made from a material with a higher ultimate tensile strength. Material properties must thus also be considered to result in functionally equivalent parts produced with IM and SLA.

4.2.4 | Conclusion of the developement of the form factor definition approach

The goal of this section was to find an approach to determine the geometric design freedom for the production of an interchangeable, functionally equivalent spare part. The explored form factor definition approach uses functional volumes and functional surfaces to define design spaces and non-design spaces in a part. These were defined after the product analysis with the geometry-based part coupling approach from section 4.1.

A case study was performed with the speed button of a Bosch hand blender. The case study showed that the form factor definition approach was capable of showing the available design freedom to produce an interchangeable, functionally equivalent spare part. This was achieved because the functional volumes define the available geometric space that the part must fit within. As long as the spare part fits within the space, it is interchangeable with the original part. The functional surfaces define the key surfaces of the part that determine its functionality. To achieve functional equivalence, the part must contain all functional surfaces. However, the functional equivalence is also dependent on the material properties of the part and if the part's geometry meets the design requirements.

4.3 | Conclusion of determining design freedom

This chapter explored two design approaches to answer the following research question:

RQ2: “Which design approaches can help a designer determine the available geometric design freedom to produce interchangeable, functionally equivalent parts with SLA and IM?”

The geometry-based part coupling approach uses graphic representations in a product architecture map to indicate the relationship of each part to its coupled parts. This approach helps a designer determine which parts of a product influence the geometry of part.

The information from the product architecture map that is composed with the geometry-based part coupling approach is used subsequently in the form factor definition approach. The form factor definition approach defines the available design space and non-design space with functional volumes and functional surfaces. The available geometric design freedom, which is what was sought after in RQ2, consists of the design space and non-design space, referred to as the 'form factor'. To produce interchangeable parts, the part must fit within the design space. The functional equivalence depends on the containment of the functional surfaces, the material properties and whether the geometry is able to meet the part’s design requirements.

5 | Designing with the available design freedom

With the available design freedom determined, the next step is to design an IM and SLA part that are interchangeable and functionally equivalent. To explore ways to do so, this chapter answers the following research question:

RQ3: "How can designers use the available design freedom as a means to produce interchangeable, functionally equivalent parts, produced with SLA and IM?"

The method that was used to explore how to use the available design freedom is stated in section 5.1. The result is shown in section 5.2. The answer to the research question is given in the conclusion in section 5.3.

5.1 | Method for the development of the form factor optimisation guide

Literature that discusses design strategies for AM was reviewed to find established design methods that are proven to be effective for part production with AM. Two main design strategies were found and analysed: a manufacturing driven design strategy and a function driven design strategy (Klahn et al., 2015). The effect of the strategies on the produced parts was examined, looking at the advantages and disadvantages of both strategies. Then, these advantages and disadvantages were related to the spare part design process, which requires designers to consider manufacturing aspects of both technologies as well as the form factor of the part. In this consideration, the limitations and opportunities from Chapter 3 and the two developed approaches from Chapter 4 are used. This information from Chapter 3 and 4 was used to compose a design guide that includes the two design strategies (manufacturing vs. function driven). The explored design guide is referred to as the 'form factor optimisation guide'. The following criteria were set for the form factor optimisation guide:

- The guide must result in parts optimised for manufacturing with IM and SLA.
- The guide uses the form factor, set by using the form factor definition approach, to allow for the production of interchangeable, functionally equivalent parts.
- The guide explores how the different limitations of each manufacturing method can be dealt with.

5.2 | Results of the development of the form factor optimisation guide

As Table 10 in Chapter 3 indicated, there is a variety of limitations for IM and SLA. Lindemann et al. (2015) state that AM offers a more design freedom than IM, but not all IM parts can be produced with AM. The limitations of SLA are mostly related to support material, uncured resin and the smaller number of available materials compared to IM.

The difference in design freedom between IM and SLA is visualised in Figure 45. The yellow bubble indicates the manufacturing capabilities of SLA, whilst the smaller red bubble indicates the more limited manufacturing capabilities of IM. The orange overlapping area is a representation of the geometries that can be produced with both technologies. For example, the steam setter holder from Chapter 3 falls in the orange area, because a geometric copy of the IM part could be manufactured with SLA. The areas of the bubbles that do not overlap represent the geometries that can only be manufactured with that technology.

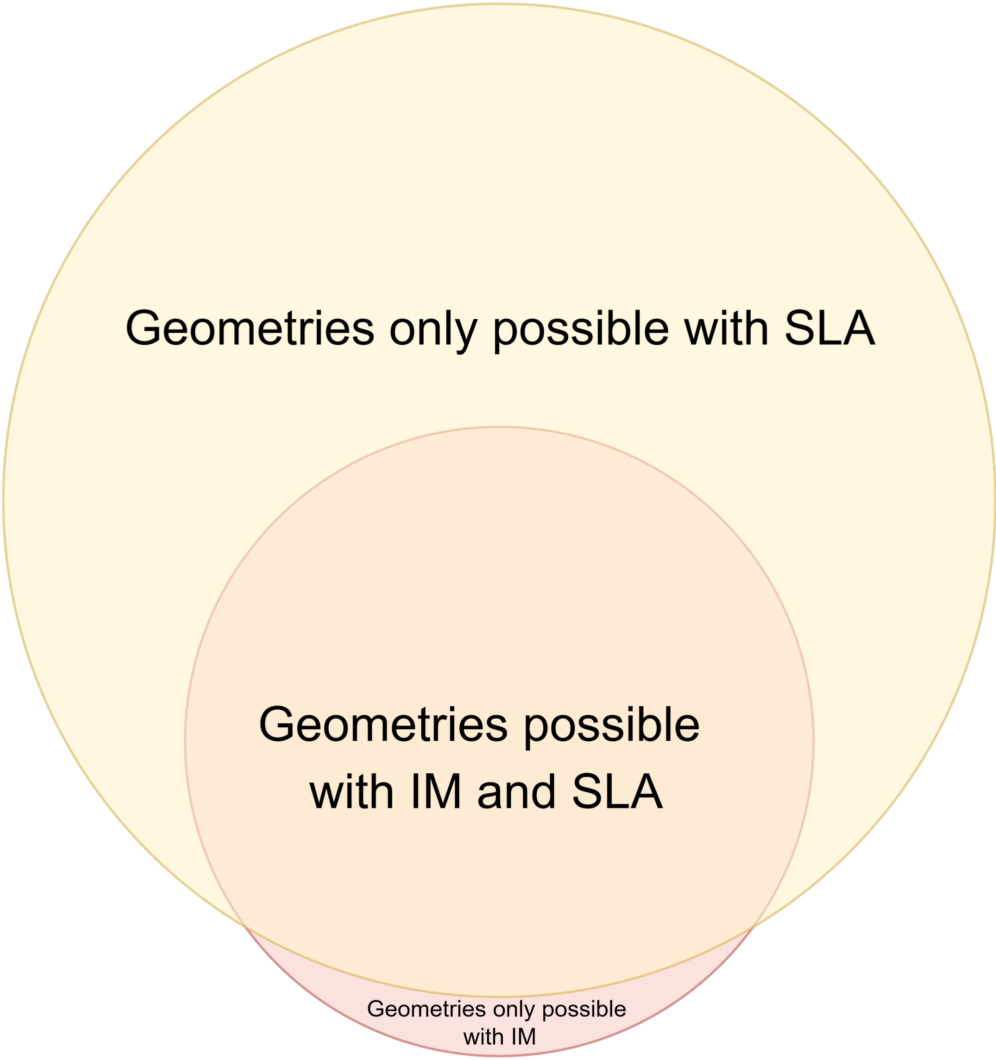


Figure 45: The overlap and difference in geometries possible with IM and SLA. Most geometries that IM can produce are also possible with SLA. Note: the visualisation is an indication and not drawn to scale.

Klahn et al. (2015) state two strategies for producing parts with AM: a manufacturing-driven strategy and a function-driven strategy. These two strategies are visualised by Diegel et al. (2019) in Figure 46, indicating that using the two different strategies can result in different designs. Klahn et al. (2015) define the two strategies as follows:

- *"By following the **manufacturing driven design strategy** the designer maintains a conventional design and complies with the design rules of other manufacturing technologies."*
- *"The **function driven design strategy** exploits the characteristics of AM to improve the functions of a product. Using the full potential of additive manufacturing's freedom in design usually rules out the transfer to conventional manufacturing without major adjustments to the design."*

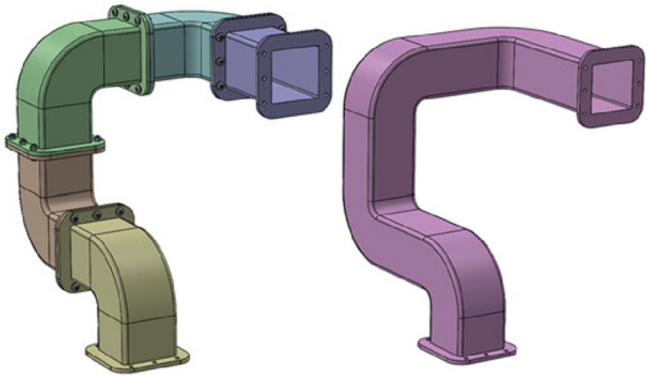


Figure 46: The manufacturing driven design strategy (left) vs. the function driven design strategy (right) applied to a product by Diegel et al. (2019). When following the manufacturing driven strategy, this assembly consists of five parts that can still be manufactured with the 'conventional' manufacturing method. Following a function driven design strategy results in one continuous AM part that eliminates all assembly steps.

When the manufacturing driven design strategy is used to produce parts designed for IM using SLA, the geometry of the IM part and SLA spare part are (close to) identical. Diegel et al. (2019) refer to this as 'direct part replacement' for identical parts, and 'adapt for AM' when changes are made to the geometry to simplify the AM manufacturing process. This places the geometry in the orange area of Figure 45. This does not use the full range of capabilities (yellow and red bubbles) that the manufacturing technologies offer. Because the limitations for both IM and SLA (Table 10) are considered in the design, rather than having two different designs, the resulting part may be suboptimal for both manufacturing technologies. Optimisations may be possible in limiting the amount of support required for the AM part for example. A possible optimisation for the IM part could be hiding the manufacturing defects.

Geometries of a part and its spare part do not have to be identical in order to be interchangeable and functionally equivalent. This was shown in the previous chapter (Figure 43). As long as the part fits within the functional volumes that define the design space, the part is interchangeable. The functional equivalence is partly dependent on the integration of the functional surfaces (the non-design space), but also on the material properties and whether the part meets its design requirements.

The function driven design strategy is seemingly the preferred approach to use in literature with AM part production (Gibson et al., 2021) (Lindemann et al., 2015) (Diegel et al., 2019). The reasons for the preference are AM's large range of manufacturing capabilities, simplification of the design process and focus on the function rather than focus on the limitations of the manufacturing capabilities, which were shown in Table 10. When using AM to produce spare parts for IM parts, the defined design space and non-design space (Chapter 4) have to be considered though. Without considering the design space and non-design space for the AM part, there is a chance that a transfer to a design that can be manufactured with IM is ruled out, as indicated by Klahn et al. (2015). In Figure 45, that would place the geometry of the part in the 'geometries only possible with SLA' section.

To get the best out of both manufacturing technologies without sacrificing the feasibility of producing interchangeable, functionally equivalent parts, a blend of the two strategies was explored. The form factor is defined with the manufacturing driven strategy, whereas the parts are optimised using the form factor with the function driven strategy. The optimisation of the parts is referred to as the 'part optimisation'.

The part optimisation is part of the newly composed guide to allow designers to design interchangeable, functionally equivalent parts with IM and SLA. This guide is referred to as the 'form factor optimisation guide' and is visualised in Figure 47. Other design approaches that were not chosen for exploration are elaborated on in Appendix G. The form factor optimisation guide is explained in the aspects after the figure.

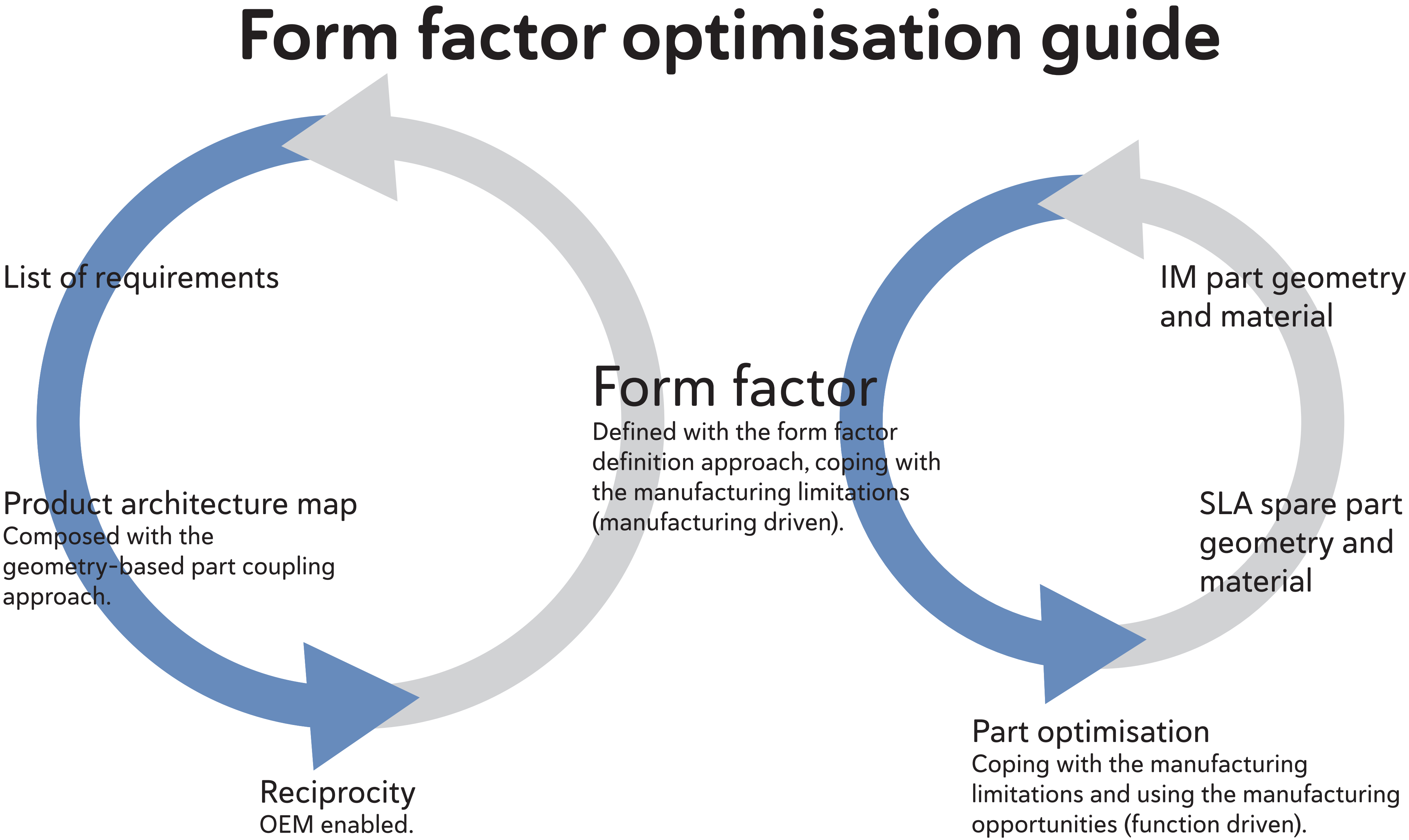


Figure 47: The newly developed form factor optimisation guide.

Form factor - manufacturing driven

The design space and non-design space (referred to as the 'form factor') of a part are influenced by the relationship of the part to its coupled parts, determined with the geometry-based part coupling approach from chapter 4.1, and the list of requirements. The form factor of the part is determined using the form factor definition approach from Chapter 4.2. Determining the form factor is a manufacturing driven process. This is because the form factor must be able to result in a part and spare part that can be manufactured with IM and SLA. The insights gathered from Table 10 in Chapter 3 provide designers guidance in what manufacturing aspects need to be considered when designing interchangeable, functionally equivalent parts with IM and SLA. Designers must constantly consider if it is possible to achieve interchangeable, functionally equivalent parts within the manufacturing capabilities of both technologies when defining the form factor.

The limitations stated in Table 10 need to be considered in different ways in the design process of interchangeable, functionally equivalent parts:

- **Limiting requirements:** When the functional equivalence or interchangeability is dependent on a design aspect that does not comply with a limiting requirement of the other technology, a redesign is needed. For example, if the functional equivalence of a part requires an intricate hollow structure, the form factor requires changes. This is because IM is not able to produce the intricate structure due to the undercuts it would create.
- **Manufacturing defects:** Manufacturing defects can be disguised in the parts if the form factor allows this. A redesign may be desired if the form factor does not allow this.
- **Potential issues:** Potential issues regarding geometry and mechanical requirements can arise when the functional equivalence or interchangeability is dependent on an aspect that falls outside the range of capabilities of the other technology. When this is the case, a redesign is needed. For example, if a part feature is not strong enough, there are two options: choosing a material with a higher ultimate tensile strength or changing the form factor that does allow the part feature to be strong enough.

If needed or desired: reciprocity

In case the defined form factor does not allow for interchangeable, functionally equivalent parts for which it is feasible to manufacture them with IM and SLA, a redesign of the coupled parts or a re-evaluation of the list of requirements for the part is needed. The process of going back and forth between the designs of the coupled parts and revising the part requirements is referred to as 'reciprocity'. The OEM process allows for this reciprocity. This is contrary to the 'consumer repair' process, where a spare part must fit within the existing product (van Oudheusden et al., 2023).

Reciprocity is initially avoided in an effort not to overcomplicate the design process for spare parts. Reciprocity is needed until a form factor is achieved that can result in interchangeable, functionally equivalent parts. Reciprocity may also be desired for optimisation purposes.

For several reasons, a certain part or technology may have priority in this reciprocity. One reason could be the fact that a part's geometry has priority over its coupled parts, because it is an off-the-shelf part. Part priority is graphically represented with arrows in the geometry-based part coupling approach (Figure 22).

Part optimisation - function driven

If a form factor is achieved that can result in interchangeable, functionally equivalent parts manufactured with IM and SLA, the next step is optimisation of the IM and SLA parts. This is a function driven process, making use of the full range of capabilities that each manufacturing technology offers. What must be considered for the part and spare part are the following:

- The material and its properties.
- Integrating all defined functional surfaces (the non-design space) in the part geometry.
- Staying within the defined design space.
- Achieving the design requirements that were set for the part.

5.3 | Conclusion of the form factor optimisation guide

This chapter aimed to explore how designers can use the available design freedom as a means to produce interchangeable, functionally equivalent parts, produced with IM and SLA. A blend of the manufacturing driven strategy and the function driven strategy defined by Klahn et al. (2015) was used in a newly composed guide for spare part design. This guide is referred to as the 'form factor optimisation guide'. The guide incorporates the previously explored geometry-based part coupling and form factor definition approaches that are used to determine the form factor. The IM part and its SLA spare part are optimised without compromising on the feasibility of producing interchangeable, functionally equivalent parts. The form factor optimisation guide also covers ways to deal with the different manufacturing limitations mentioned in Table 10.

6 | Case study pen

In this chapter, the form factor optimisation guide as described in Chapter 5 was applied to a case study with the pen shown in Figure 48. This case study was performed to see how the guide could result in distinct designs of interchangeable, functionally equivalent parts produced with IM and SLA.

The problem of the current pen design is in the connection of the pen tip to the housing. The pen tip is connected with a screw thread to the housing of the pen (Figure 49). A problem can occur when the screw thread of the pen tip is over tightened on the pen's housing. This may cause the housing of the pen to tear (Figure 50). As a result of the pressure on the pen tip by the spring inside, the pen tip may get pushed away, compromising the functionality of the pen. The goal of the case study is to design a spare housing that can be connected to the pen tip. The case study is scoped to the design of the pen tip and pen housing and should yield interchangeable, functionally equivalent parts, produced with IM and SLA.

Figure 48: The pen that was redesigned in this case study.

Figure 49: The pen tip has screw thread to connect it to the housing of the pen.

Figure 50: When the screw thread of a pen is overtightened, the pen housing can tear.

6.1 | Method for the pen redesign

The steps taken in the pen redesign process were part of the composed form factor optimisation guide. It consisted of the following steps:

1. Set up a list of requirements for the new design of the pen tip and housing. The used method was the MoSCoW prioritisation method (Agile Business Consortium Limited, 2025). This method differentiates three priority levels of requirements: Must have's, Should have's and Could have's. Furthermore, it mentions 'Won't have's', listing the aspects of the design problem that are out of scope. Setting up this list of requirements included an analysis of the way the pen is currently manufactured.
2. Compose a product architecture map, using the geometry-based part coupling approach from Chapter 4.1. For the component lay-out on the map, a disassembly map of the pen was made, using the Disassembly Map method by De Fazio et al. (2021).
3. Define the form factor (design space and non-design space), using the form factor definition approach from Chapter 4.2. All parts besides the pen tip and housing were considered fixed.
4. Determine whether reciprocity is required between the coupled parts and apply it. This was determined by analysing the current pen design and checking whether a spare part could be manufactured within the limitations stated in Table 10.
5. Redesign the troublesome parts within the established form factor, with a function driven design strategy. The parts were modelled using

SolidWorks 2023 CAD software. The pen was measured with callipers to base the design on. Early prototypes were made on a Creality Ender 3V2 FDM printer with PLA filament on a 4:1 scale (Appendix H). FDM was used instead of SLA to decrease the waiting time for the prototypes. A 4:1 scale was used so the designs could be manufactured with FDM. After an iteration, the parts were produced with SLA using the Formlabs Form 3+ printer with Tough 1500 resin (Formlabs, 2024a), to be able to test the prototypes at the desired part quality.

The multiple design concepts that were explored were assessed based on the list of requirements.

6.2 | Results of the pen redesign

6.2.1 | List of requirements

The list of requirements in Table 13 was composed using the MoSCoW method (Agile Business Consortium Limited, 2025).

Table 13: The list of requirements for the pen tip and housing design, composed using the MoSCoW method (Agile Business Consortium Limited, 2025).

Requirement category	Requirement	Requirement abbreviated
Must have	The parts can be manufactured within the limitations of the current manufacturing technology (Appendix H)	Part feasibility
	The spare housing can be manufactured within the limitations of SLA.	Spare part feasibility
	The pen tip stays in place under the pressure of the spring, resulting in functional equivalence.	Functional equivalence
	The housing and spare housing are interchangeable.	Interchangeability
	The design of the connection between the pen tip and housing prevents splitting of the housing.	Housing splitting
Should have	Disassembly and assembly are possible with hand motion, for user experience.	Hand motion (dis) assembly
	Disassembly and assembly can be repeated >10 times without compromising functionality, so the ink cartridge can be replaced.	(Dis)assembly repeatability
	No changes are made to the parts outside of current mould designs (Appendix H), for the viability of the part.	Part viability
	No additional post-processing is required for the spare parts besides support removal, for the viability.	Post-processing viability
Could have	No additional parts are added, for the viability of the product.	Additional parts
	Parts that are not custom-IM parts are not changed, to limit the number of changes required to the product for the viability.	Changes to not custom-IM parts
Won't have	No changes are made to the manufacturing method of the parts.	Manufacturing method
	No changes are made to the current selection of off-the-shelf parts.	Off-the-shelf parts

6.2.2 | Product architecture map

The pen was disassembled for part analysis. The name of each part is annotated in Figure 51.

After composing the disassembly map of the pen, the product architecture map was composed. These maps are shown in Appendix H. The information that influences the design of the tip-housing connection is shown in Figure 52. It shows that:

- The pen tip is considered a custom non-IM part, indicated by the green rectangle. This is because the pen tip is made from metal, not plastic. The housing is a plastic custom IM part, indicated by the red rectangle.
- The pen tip and housing are coupled with a 'static' coupled interface type, indicated with the black line colour. This means that there is no movement of the pen tip and housing relative to the product. There is no form of geometry priority, as indicated by the lack of an arrowhead.
- The pen tip and spring are coupled with a 'relative displacement' coupled interface type, indicated with the green line colour. The spring can move within the pen tip without moving the pen tip. The spring also has geometric and positional priority over the pen tip, as indicated with the solid arrowhead.
- The housing and pen tip come in contact with the user during regular use, as indicated by the human figure icon.

Figure 51: All parts of the pen annotated with their name.

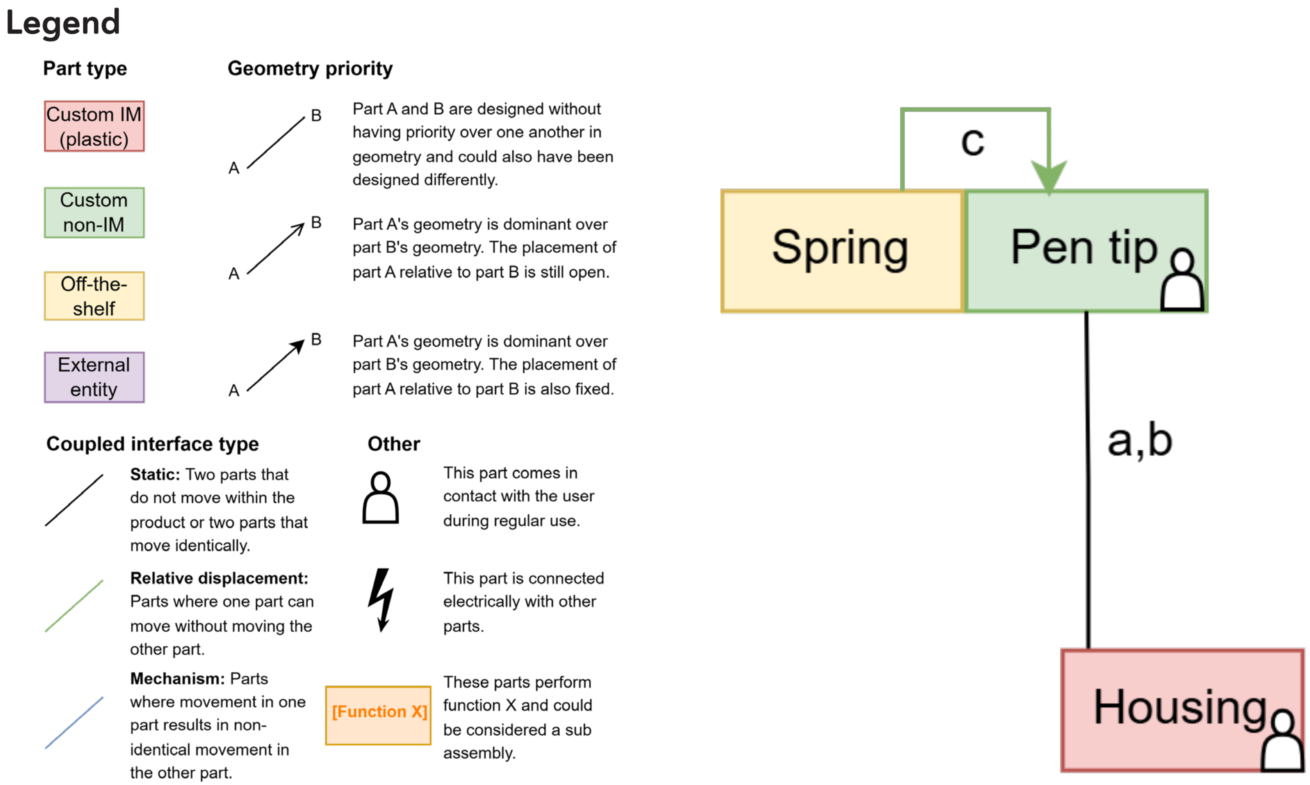


Figure 52: A partial product architecture map of the pen with the components involved in the case study. The map was composed with the geometry-based part coupling approach and is annotated with the functional surfaces from the form factor.

6.2.3 | Form factor definition

The analysis of the geometry of the parts showed that the non-design space is defined by the following functional surfaces:

a. A transition fit between the pen tip and housing.
b. Matching diameters of the pen tip and housing.
c. A clearance fit with between the pen tip and spring diameter.

The design space and non-design space were mapped over the model of the pen tip and housing in Figure 53. For the full form factor of the pen tip, see Appendix H. The annotated product architecture map (Figure 52) shows which coupled parts result in which functional surfaces.

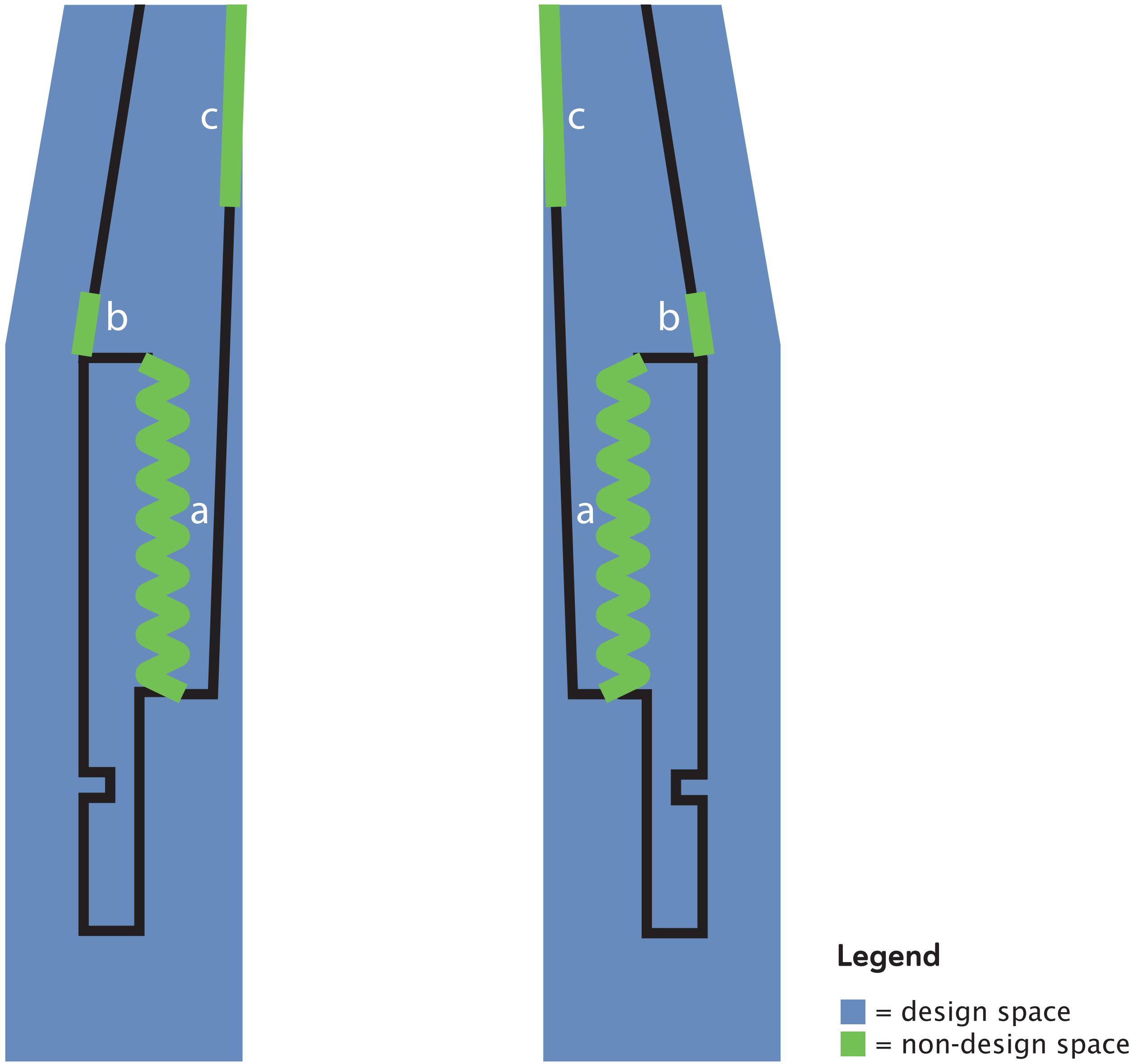


Figure 53: The form factor of the pen tip and housing combined.

6.2.4 | Reciprocity

Producing a functionally equivalent copy of the pen tip in SLA was not possible within the existing form factor. The details of the screw thread that that made up functional surface a were too weak. Printing thread sizes under M6 are not recommended by Formlabs (Formlabs, 2025c). As shown in Figure 54, the thread size of the pen tip is much smaller than that of an M6 bolt. The thread size is M3x0.5, cut from a 6.82 mm diameter.

The lack of functional equivalence was confirmed with prototypes. An identical copy of the pen housing and tip could be manufactured with SLA (Figure 55), as expected based on the limitations determined in Table 10. The details are namely not smaller than 0.1 mm. However, when the pen tip was inserted in the housing (Figure 56), the screw threads quickly wore out and stripped. The lack of mechanical strength of the part thus compromised the functionality of the pen. A different design was thus required that does not depend on the use of M6 screw thread, as an alternative for the current functional surface a that connects the pen tip to the housing. Functional surface b and c can stay the way they are.

Figure 56: The original pen tip inserted in the SLA housing.

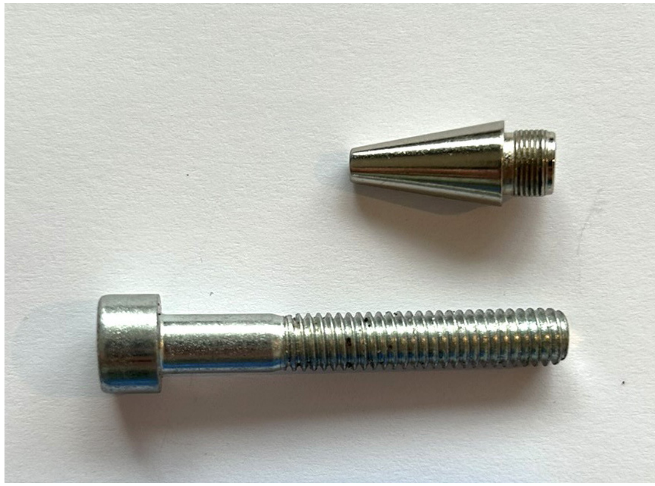


Figure 54: Comparison of the pen tip's screw thread to an M6 bolt, clearly showing that the pen tip's screw thread is much smaller.

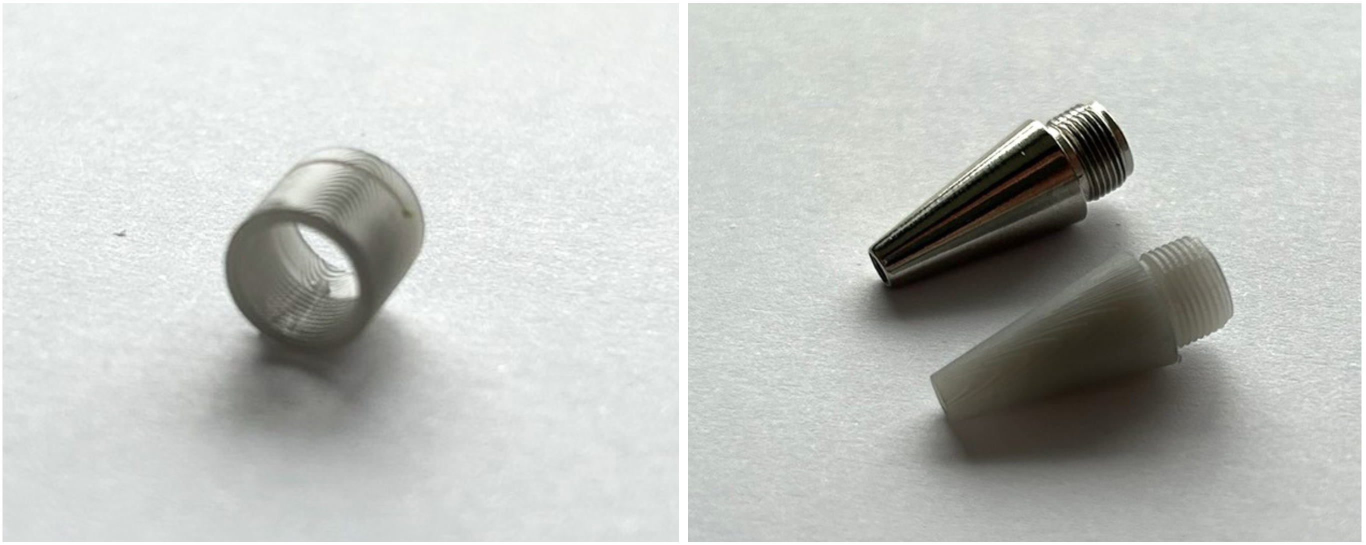


Figure 55: Identical copies of the top part of the housing (left) and the pen tip (right) were manufactured with SLA.

6.2.5 | Redesign concepts of pen tip connection to the housing

Various ideas were generated (Appendix H). The first concept that was explored was the use of a custom, **courser thread size**. This idea was inspired by the coarse thread size from another pen (Figure 57). The newly modelled thread size on the pen tip and housing (Figure 58) is M6, cut from the original pen tip diameter of 6.82 mm, with a thread pitch of 1.50 mm. The coarser thread was applied to both the pen tip and housing, meaning the design of both parts is changed compared to the original pen. The new IM parts and SLA spare parts are identical in geometry. The pen tip and housing were manufactured with SLA (Figure 59). This resulted in a connection that is strong enough to keep the two parts together (Figure 60).

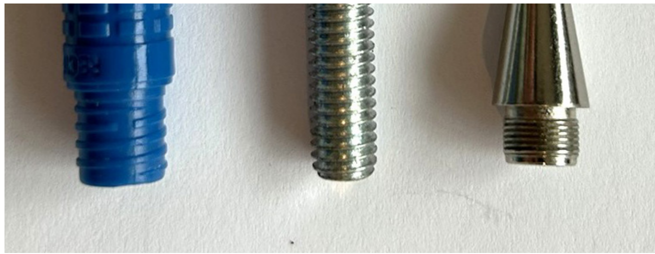


Figure 57: Courser threads on pens already exist (left) and are much coarser than M6 thread (middle) or the pen tip from the case study (right).

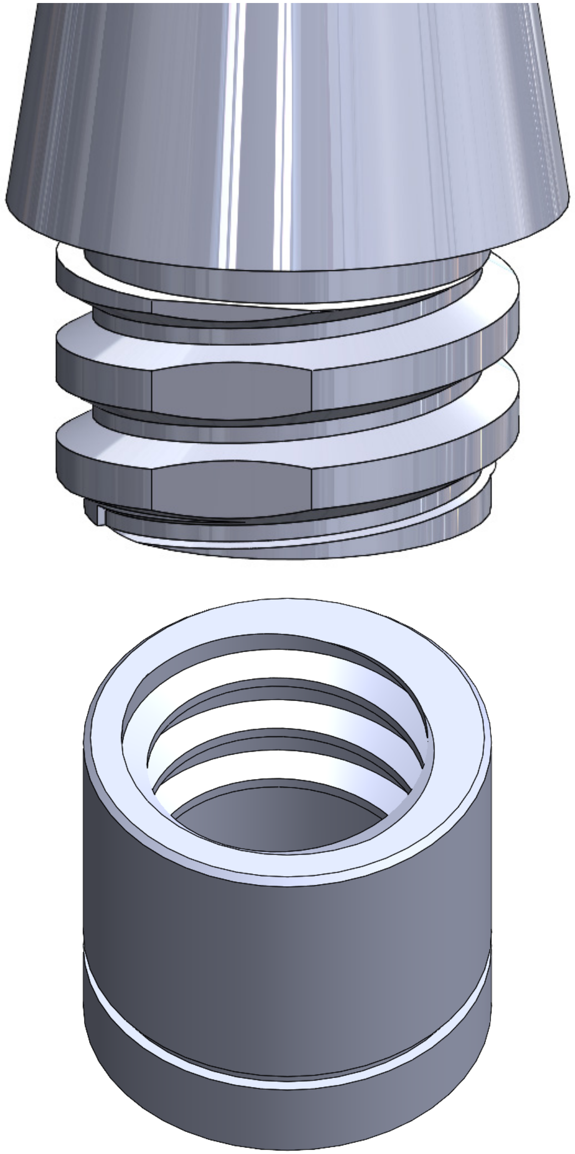


Figure 58: The pen tip (top) and housing (bottom) modelled with coarser threads.

Figure 59: The pen tip (top) with coarse threads and the corresponding pen housing (bottom) manufactured with SLA.

Figure 60: The pen tip and housing partly assembled.

The second concept that was explored was the use of a **transition fit** to keep the pen tip and pen housing together. The housing is modelled without any threads, to a diameter 0.02 mm larger (6.84 mm in total) than the pen tip (Figure 61). As a result, the original pen tip (with screw threads) can be inserted in the SLA housing with a transition fit (Figure 62) that keeps both parts together. In this concept, there is thus a difference in the design of the IM housing and SLA housing, whilst the IM pen tip design is not changed.

The third concept that was explored was **tapping threads** in the housing **during post-processing**. The housing was modelled without threads (Figure 63), so these can be added during post-processing. This means that the designs of the IM housing and SLA spare housing are different initially, but identical after post-processing. For more information regarding the post-processing of the SLA prototype, see Appendix H.

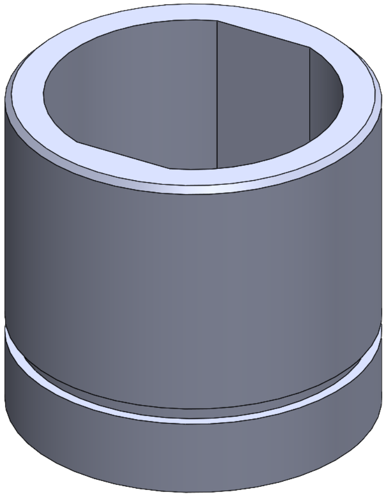


Figure 61: The housing modelled (top) and manufactured with SLA (bottom) for a transition fit with the existing pen tip.

Figure 62: The original pen tip inserted in the SLA housing with a transition fit.

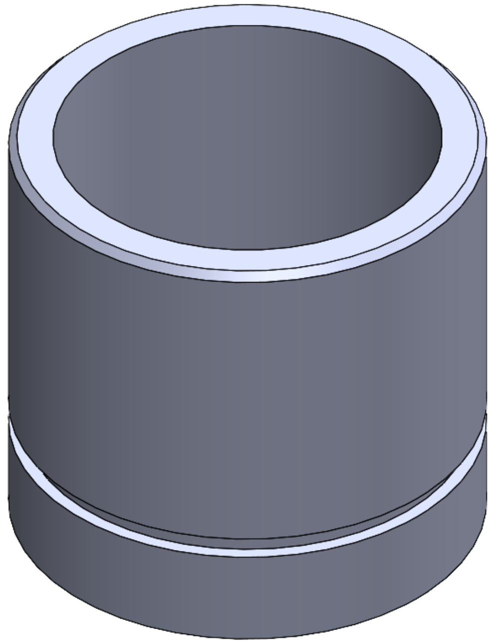


Figure 63: The pen housing modelled for post-processing screw threads.

The fourth and final concept that was explored was the use of a **bayonet closure** in combination with the original screw thread on the pen tip. The newly designed pen tip and spare housing are shown in Figure 64. The IM housing's design stays the way it is (with the fine screw threads). The SLA spare housing's design has two outdents on the inside of the housing and no screw thread. A J-shape track was added to the screw threads in the original metal pen tip, which follows the outdents in the spare housing during assembly. Within the J-shape track, an outdent is also added so that the outdent of the housing snaps in place firmly.

This redesign allows the pen tip to connect to the IM housing with the fine screw thread but connect to the SLA spare housing with the bayonet closure. The design of the pen tip and housing were manufactured with SLA (Figure 65) to test the functionality of both connections (Figure 66). Both connections functioned adequately, though again, the printed threads were prone to wear. For more information regarding the design process, see Appendix H.

An alternative solution for this fourth concept would be to solely use a bayonet closure, also in the IM housing. However, this would have required the addition of side slides to the mould, in order to allow for the production of the outdents. This would have meant that the 'part viability' requirement was not met.

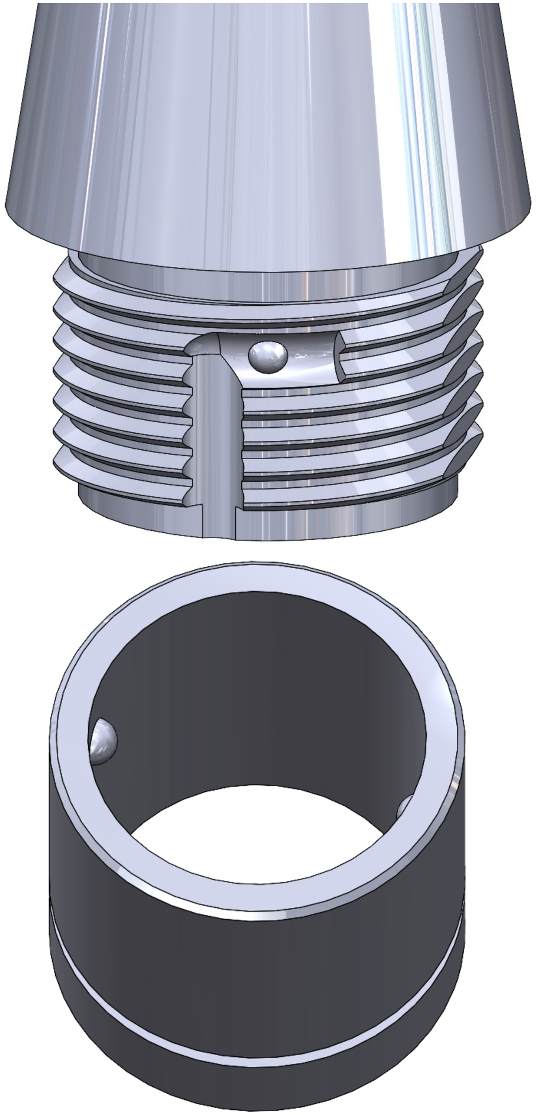


Figure 64: The newly designed pen tip and spare housing. The outdents of the spare housing ride in the J-slot of the pen tip to lock the pen tip to the spare housing.

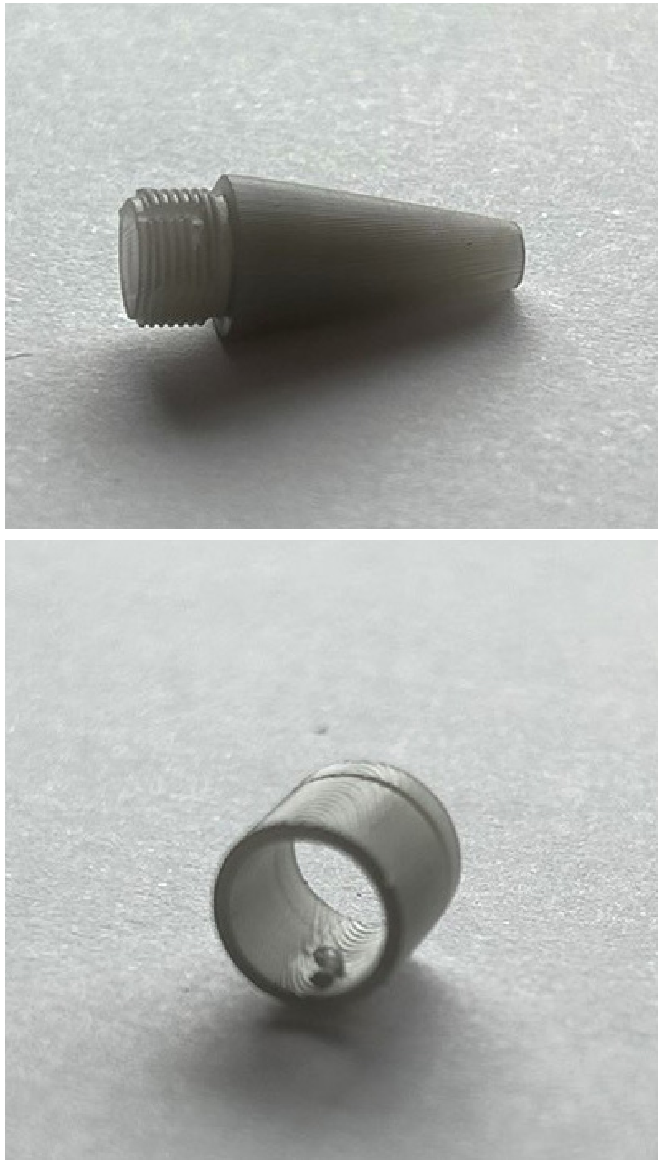


Figure 65: The new pen tip (top) and spare housing (bottom) manufactured with SLA.

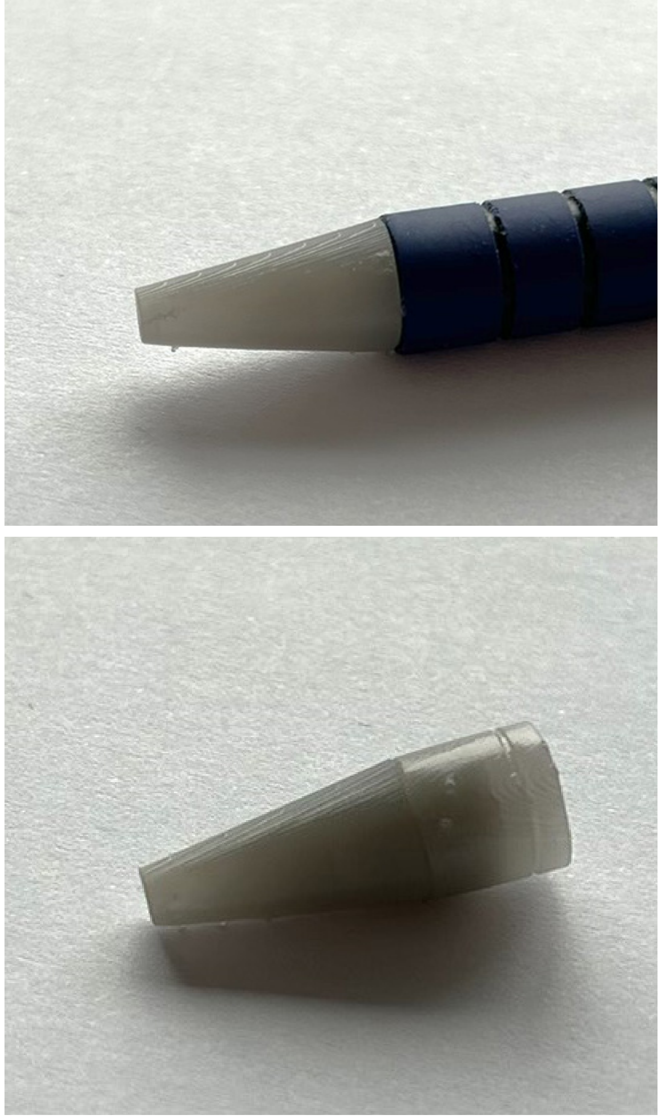


Figure 66: The same pen tip assembled with the original IM housing with screw thread (top) and assembled with the bayonet closure in the SLA spare housing (bottom).

6.2.6 | Concept assessment

All four redesign concepts for the connection of the pen tip to the housing were assessed in Table 14 based on the list of requirements from Table 13. The assessment of all four concepts on the design requirements shows that none of the four concepts meets all design criteria. However, looking at the priority of the requirements, this is the order of the best to worst scoring concepts:

1. **Bayonet closure:** one 'Could have' requirement that is not met, because a change is made to the not custom-IM pen tip.
2. **Course thread:** one 'Must have' requirement that is possibly not met, one 'Could have' requirement that is not met. This is because the housing may still be prone to splitting due to the use of a screw thread and the not custom-IM pen tip is changed.
3. **Post-process tap thread:** one 'Must have' requirement that is possibly not met, one 'Should have' requirement that is not met. This is because the housing may still be prone to splitting due to the use of a screw thread and the threads are made with an additional post-

Table 14: Assessment of the four pen redesigns based on the list of requirements. Green = meets requirement, yellow = possible issues in meeting the requirement, red = does not meet requirement.

Requirements		**Concepts**			
Requirement category	**Requirement abbreviated**	**Course thread**	**Transition fit**	**Post-process tap thread**	**Bayonet closure**
Must have	Part feasibility				
	Spare part feasibility				
	Functional equivalence				
	Interchangeability				
	Housing splitting				
Should have	Hand motion (dis)assembly				
	(Dis)assembly repeatability				
	Part viability				
	Post-processing viability				
Could have	Additional parts				
	Changes to not custom-IM parts				
Won't have	Manufacturing method				
	Off-the-shelf parts				

processing step.

4. **Transition fit:** one ‘Must have’ requirement that is possibly not met, one ‘Should have’ requirement that is not met and one ‘Should have’ requirement that is possibly not met. This is because the transition fit is hard to disassemble with hand motion at first, but may wear over time, compromising the functionality and (dis)assembly repeatability.

6.3 | Conclusion of the pen redesign case study

The goal of this case study was to see how distinct designs can follow from applying the form factor optimisation guide in the design process of interchangeable, functionally equivalent parts. Four design concepts were explored using the form factor optimisation guide that meet most of the requirements from Table 13.

For this relatively simple product, the geometry-based part coupling approach was helpful, but not required. Because the pen only contains seven parts, it was easy to comprehend how these parts must be able to fit within the product. On the other hand, because the product only contained seven parts, the product architecture map was quick and easy to make and provided a clear overview of the geometric relationships between the coupled parts of the pen.

Defining the form factor provided a clear starting point for the design process. After soon realising that the form factor would not allow for an interchangeable, functionally equivalent spare part manufactured with SLA, reciprocity between the designs of the neighbouring was applied. Here the result of tackling this design problem from an OEM perspective is shown. If this reciprocity would not have been possible, the course thread concept and bayonet closure concept would not have been an option, eliminating the two best scoring concepts.

Overall, the form factor optimisation guide was used as an optional tool, not as a strict ruleset to follow. The four design concepts show that different form factors can all provide valid solutions, so there is not ‘one best way’ to go about the design process. The form factor optimisation guide should be applied when deemed necessary by the designer.

7 | Case study snap fits

In this chapter, the form factor optimisation guide as described in Chapter 5 was applied to a case study with the steam setter holder shown in Figure 67. This case study was performed to see how the guide could be used to redesign a complex part that is coupled to many parts, resulting in interchangeable, functionally equivalent parts produced with IM and SLA.

In section 3.2.2, a geometric copy was produced of the IM steam setter holder. However, one of the issues to explore was the uncertainty of the part performance over time due to plastic deflection of the snap fits, caused by creep and being under constant load. Added was the uncertainty of the part performance over time due to exposure to UV light and becoming brittle (Formlabs, 2025a). Amaya Rivas et al. (2024) have explored producing snap fits with SLA. This case study explored how the form factor optimisation guide could be used to redesign the steam setter holder in a way that eliminates the snap fits in the part (Figure 68):

1. The snap fits that connect the steam setter holder to the top shell.
2. The snap fits that connect the steam setter holder to the top cover.

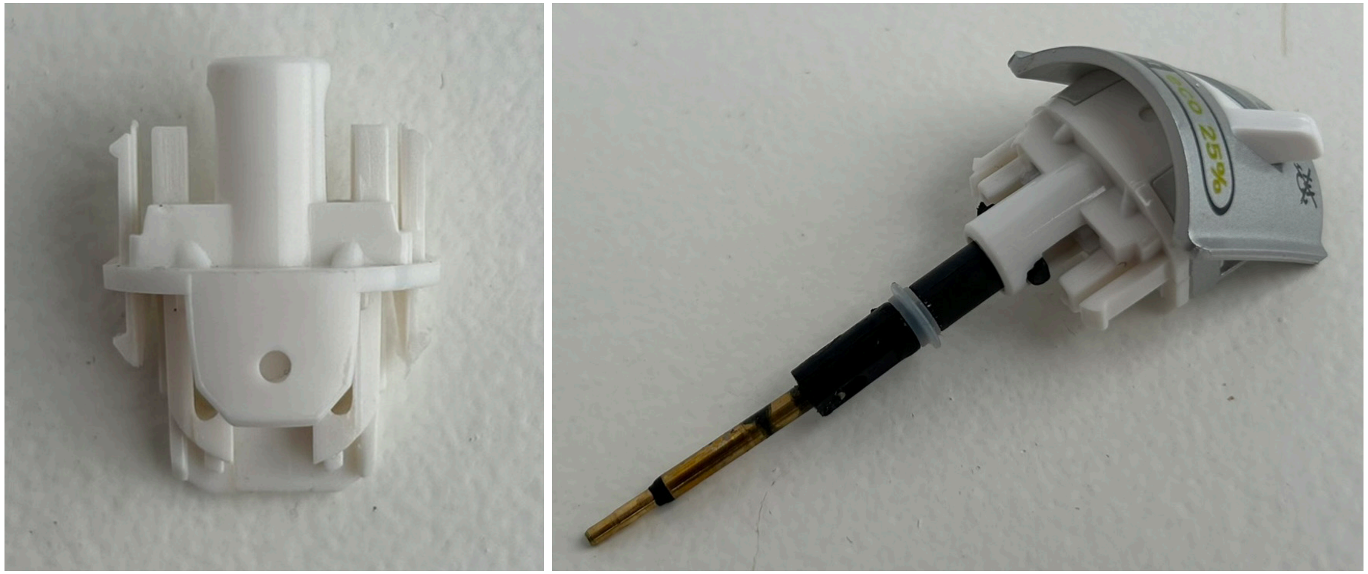


Figure 67: The steam setter holder.

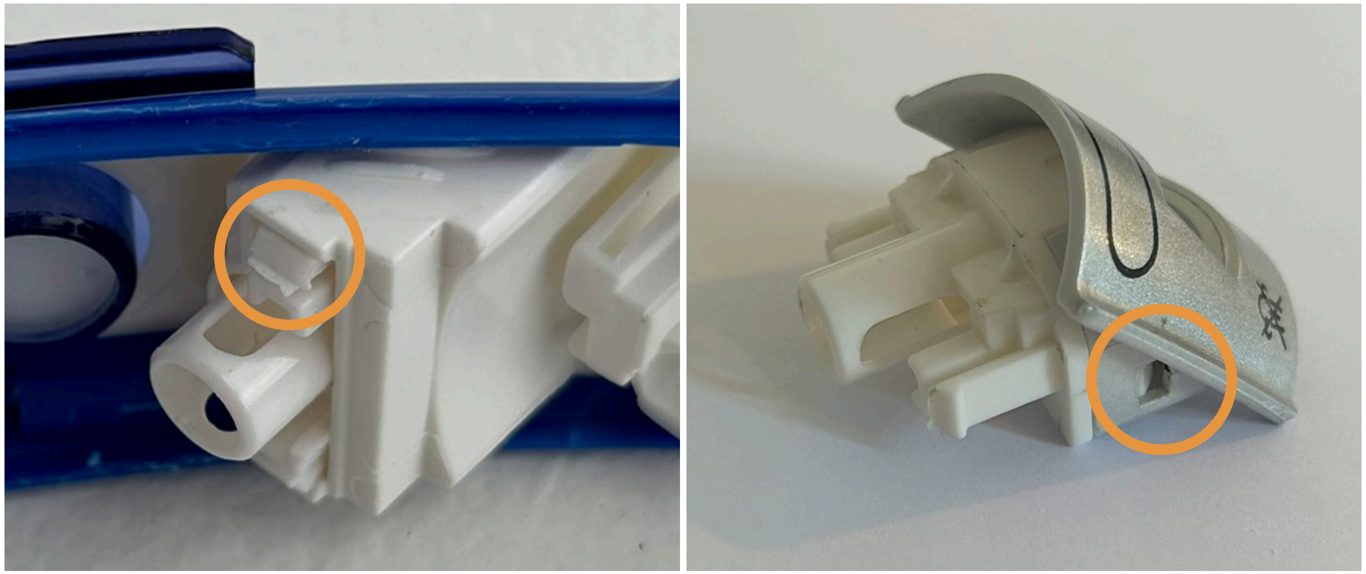


Figure 68: The snap fits that were redesigned in this case study.

7.1 | Method for the snap fits redesign

The steps taken in the snap fit redesign process were part of the composed form factor optimisation guide. It consisted of the following steps:

1. Set up a list of requirements for the new design of the steam setter holder. The used method was the MoSCoW prioritisation method (Agile Business Consortium Limited, 2025). Setting up this list of requirements included an analysis of the way the pen is currently manufactured.
2. Compose a product architecture map, using the geometry-based part coupling approach from Chapter 4.1. For the component layout on the map, a disassembly map of the steam setting assembly was made, using the Disassembly Map method by De Fazio et al. (2021).
3. Define the form factor (design space and non-design space), using the form factor definition approach from Chapter 4.2. All parts besides the steam setter holder, top cover and top shell were considered fixed. Determining whether reciprocity was required was done by ideating designs and checking whether a spare part could be manufactured within the form factor, coping with the limitations stated in Table 10.
4. Redesign the troublesome parts within the established form factors, with a function driven design strategy. The parts were modelled using SolidWorks 2023 CAD software. The parts were measured with callipers to base the design on. Early prototypes were made on a Creality Ender 3V2 FDM printer with PLA filament on a 1:1 scale (Appendix I). FDM was used to decrease the waiting time for the prototypes. After an iteration, the parts were produced with SLA using the Formlabs Form 3+ printer with Tough 1500 resin (Formlabs, 2024a), to assess the part with the desired quality.

The explored concept was assessed on the list of requirements afterwards.

7.2 | Results of the snap fits redesign

7.2.1 | List of requirements

The list of requirements in Table 15 was composed using the MoSCoW method (Agile Business Consortium Limited, 2025).

Table 15: The list of requirements for the steam setter holder redesign, composed using the MoSCoW method (Agile Business Consortium Limited, 2025).

Requirement category	Requirement
Must have	The parts can be manufactured within the limitations of the current assembly method. All parts for this case study are plastic injection moulded parts.
	The spare part can be manufactured within the limitations of SLA.
	The user can set the steam function in three settings (functional equivalence).
	The part and spare part are interchangeable.
Should have	The steam setting assembly can be taken out with hand motion. This is because the user needs to remove the assembly monthly for cleaning (Tefal, 2024).
	Disassembly and assembly can be repeated >50 times without compromising functionality. This is because the assembly needs to be removed monthly for cleaning (Tefal, 2024).
	The part can be manufactured within the current mould designs (Appendix I), for viability.
	No additional post-processing is required for the spare parts besides support removal, for the viability.
Could have	No additional parts are added, for the viability of the product.
	Parts that are not custom-IM parts are not changed, to limit the number of changes required to the product for viability.
Won't have	No changes are made to the manufacturing method of the parts.
	No changes are made to the current selection of off-the-shelf parts.

7.2.2 | Product architecture map

The steam setting assembly was disassembled during the disassembly of the Tefal iron (Appendix C). After composing the disassembly map of the pen, the product architecture map was composed. These maps are shown in Appendix I. The information that influences the design of the snap fits is shown in Figure 52. It shows that:

- The steam setter holder, top cover and top shell are plastic custom IM parts, indicated by the red rectangles.
- There is no form of geometry priority between the three parts, as indicated by the lack of an arrowhead.
- The steam setter holder, top cover and top shell are all coupled with a 'static' coupled interface type, indicated with the black line colour. Even though the steam setting assembly is removable from the top shell with the snap fits, it is considered static during regular use.
- The top cover and top shell come in contact with the user during regular use, as indicated by the human figure icon.

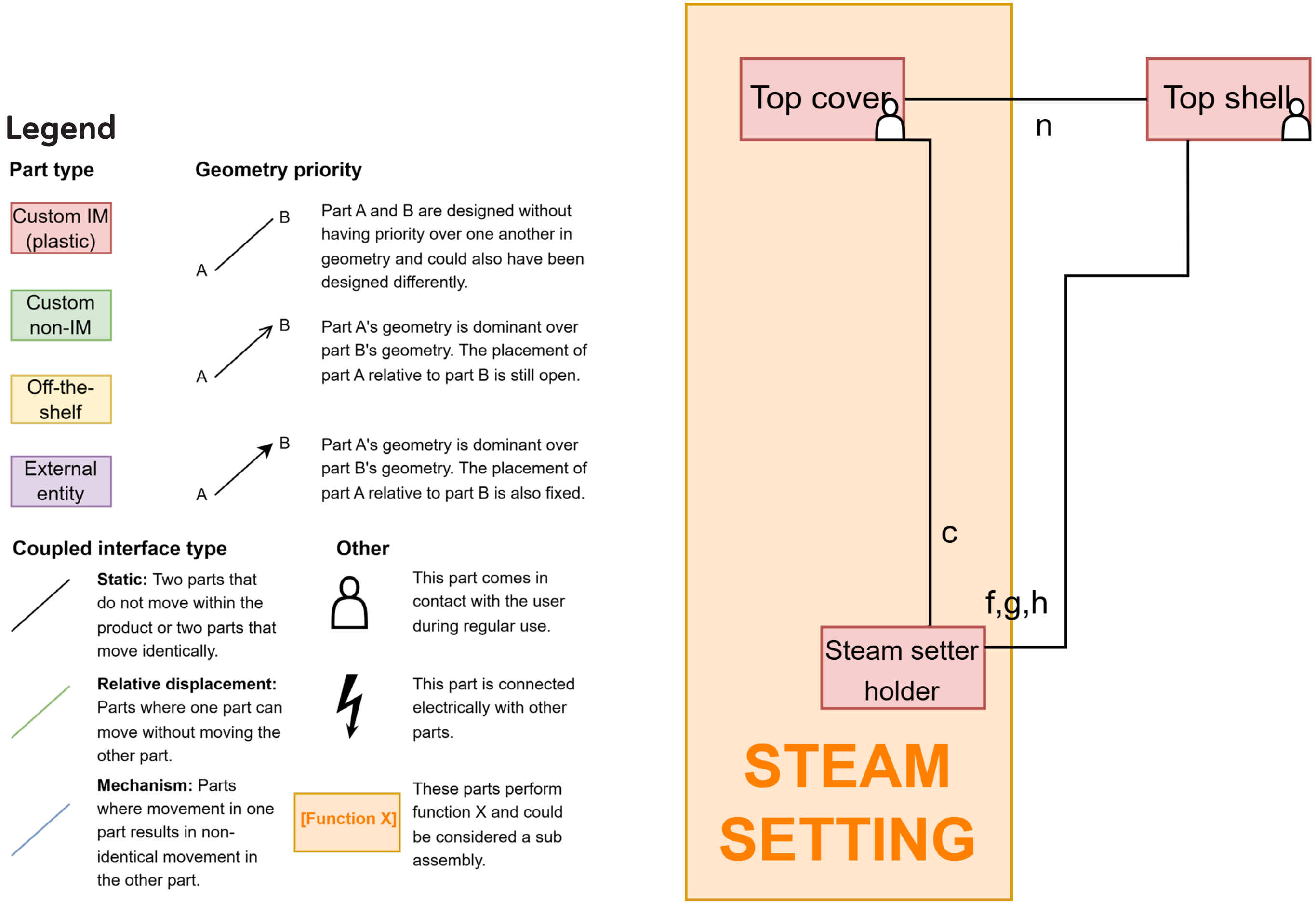


Figure 69: The product architecture map of the parts included in the case study, composed with the geometry-based part coupling approach. The map is annotated with the functional surfaces from the form factors.

7.2.3 | Form factor and reciprocity

During ideation (Appendix I), it became apparent that solely redesigning the steam setter holder within its form factor (Figure 70) would not allow for an interchangeable, functionally equivalent spare part. There was not enough design freedom to attach the steam setter holder to the top shell in a different manner. Therefore, reciprocity was applied and the form factor of the top shell was also included for the redesign (Figure 71).

The functional surfaces that define the connections between the steam setter holder, top cover and top shell are:

c. A surface for the steam setter holder to hook around the top cover.
f. A transition (snap) fit between the steam setter holder and the top shell.
g. A transition fit between the steam setter holder and the top shell.
h. A transition fit between the steam setter holder and the top shell.
n. A clearance fit between the top cover and top shell.

The functional surfaces were also mapped in the product architecture map (Figure 69). The top cover's form factor is not included because its design was not changed. Elaboration of all functional surfaces of the steam setter holder can be found in Appendix I.

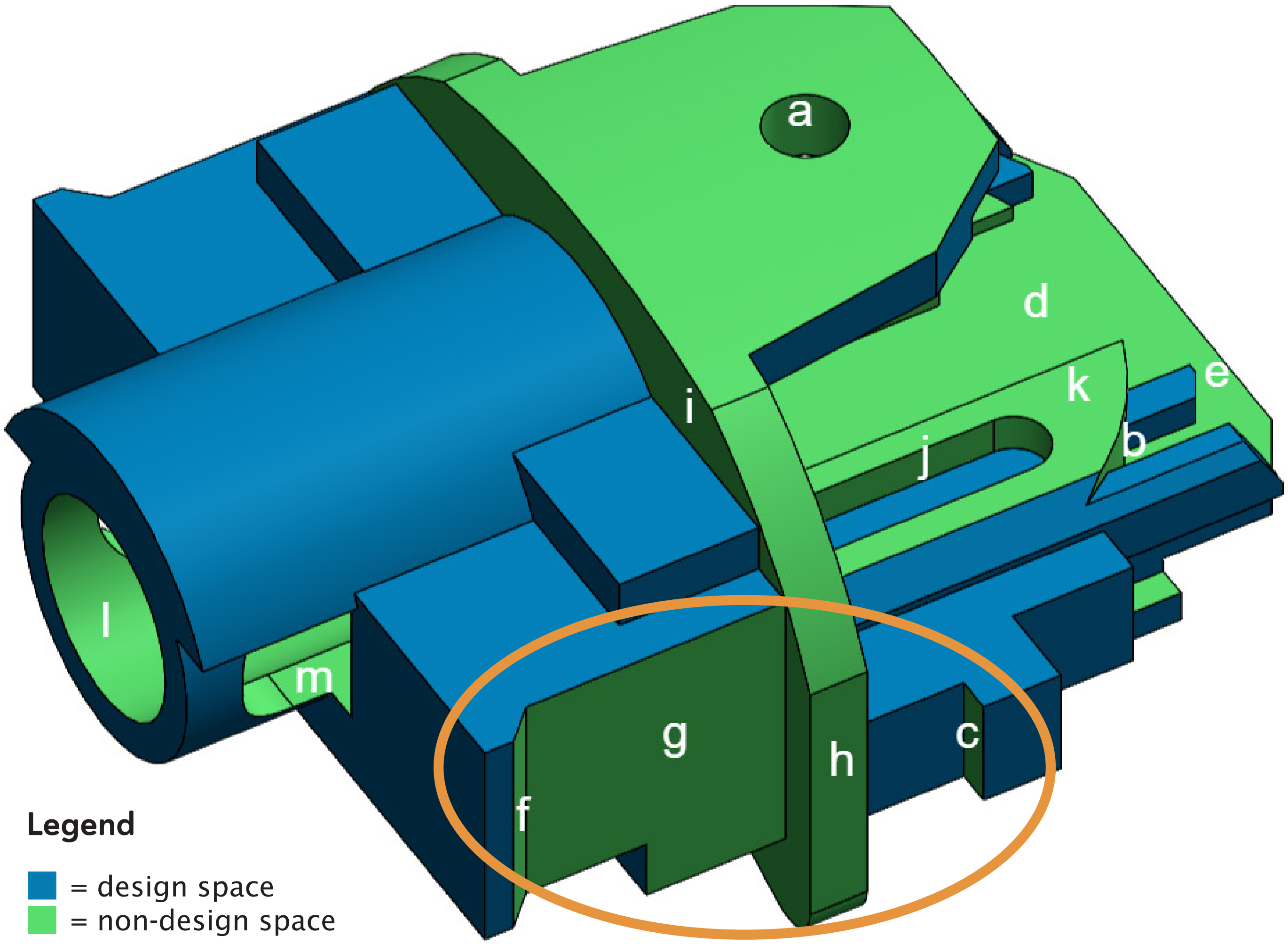
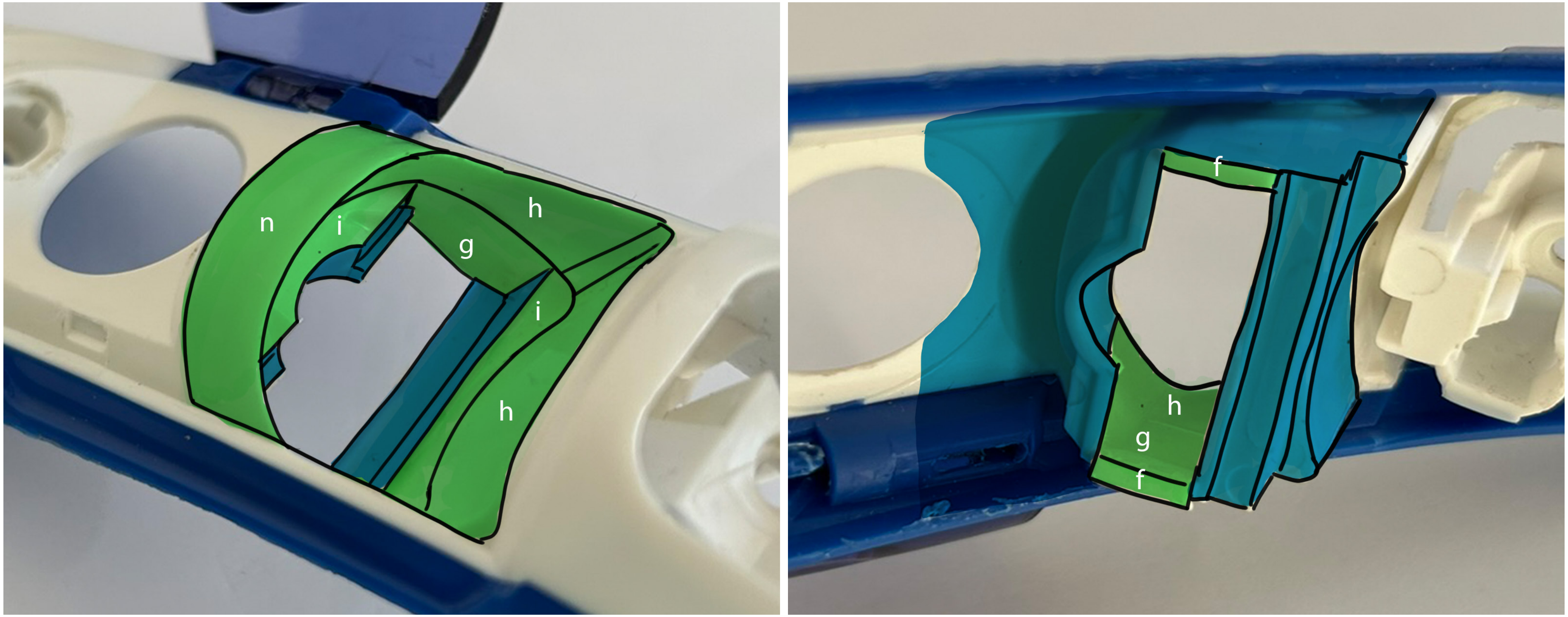


Figure 70: The form factor of the steam setter holder.



Legend

= design space
= non-design space

Figure 71: The form factor of the top shell.

7.2.4 | Redesigns of the snap fits

The explored spare part design of the steam setter holder uses set screws to connect the steam setter holder to the top cover and top shell (Figure 72). With this redesign, the assembly is still interchangeable and functionally equivalent with the original assembly (Figure 73).

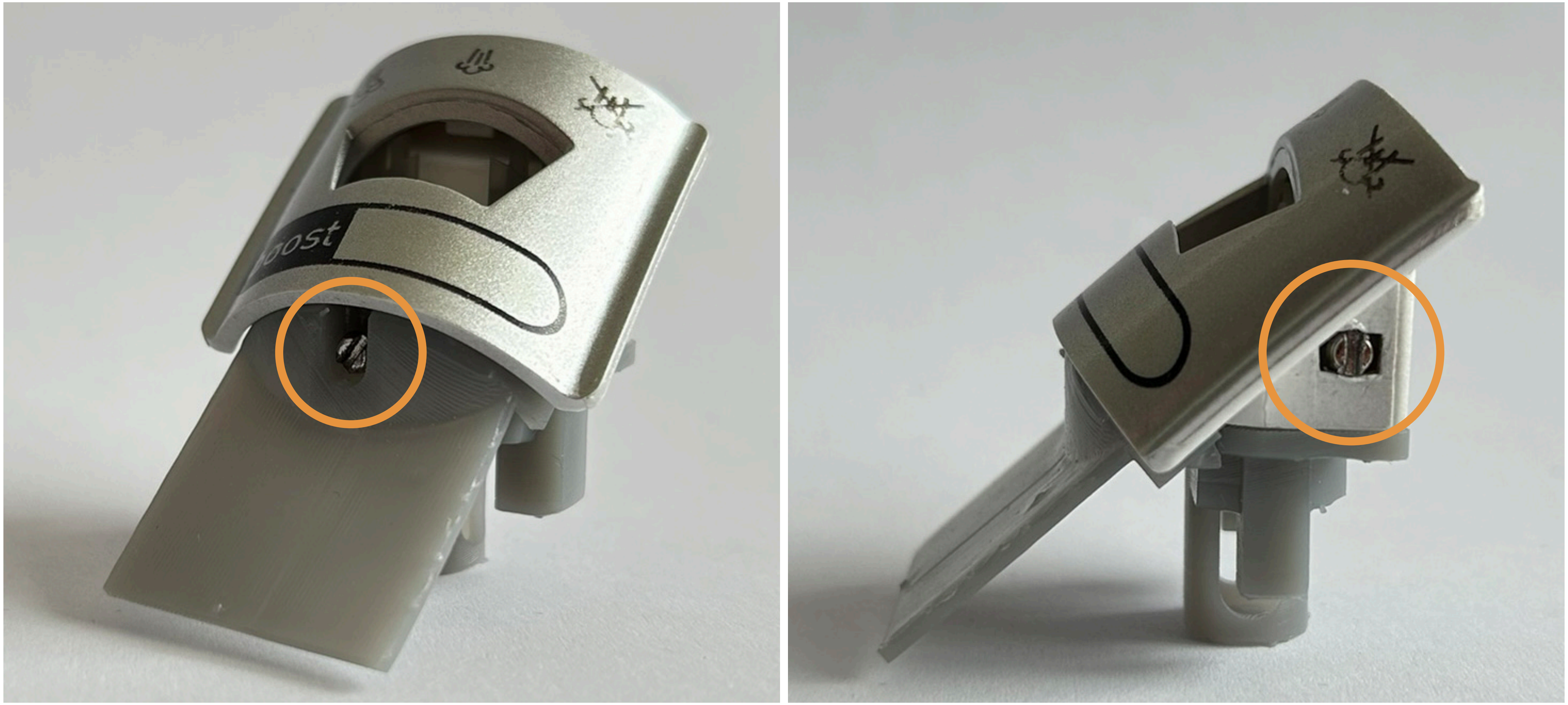
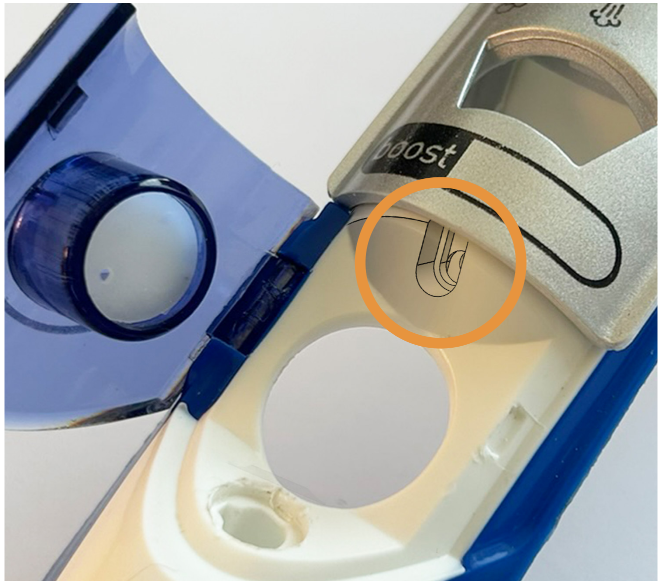


Figure 72: The assembly of the spare steam setter holder, top cover and the adjusted top shell. Only part of the top shell was produced.

Figure 73: The spare parts are interchangeable and functionally equivalent with the original assembly.

The new connections are enabled by adding three holes to the steam setter holder: two on the side and one on the top (Figure 74). A slot and a hole were added to the stop shell (Figure 75), which are hidden to the user during regular use by closing the blue hinging cover. The slot and hole can created with the current mould design layout (Appendix I), because all new features can be created with vertically moving mould halves (Figure 76).



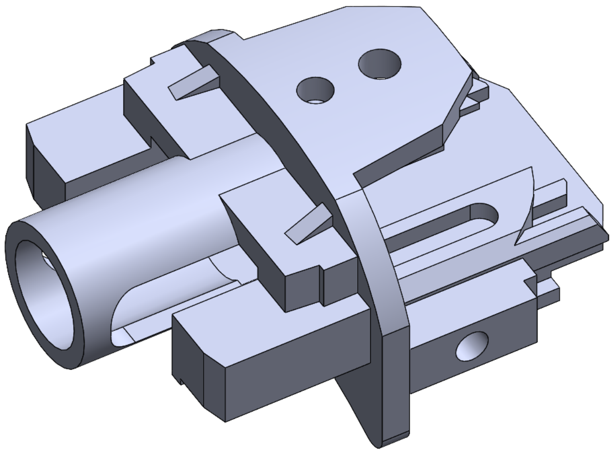


Figure 74: The steam setter holder spare part design. A third hole is added to the part on the left side, symmetrical to the hole on the right side. The snap fits have been swapped out for features that are just there for alignment.

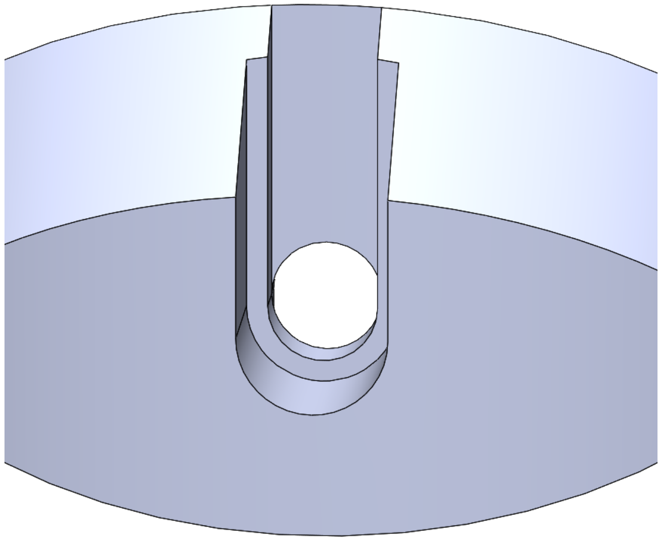


Figure 75: The adjusted top shell design.

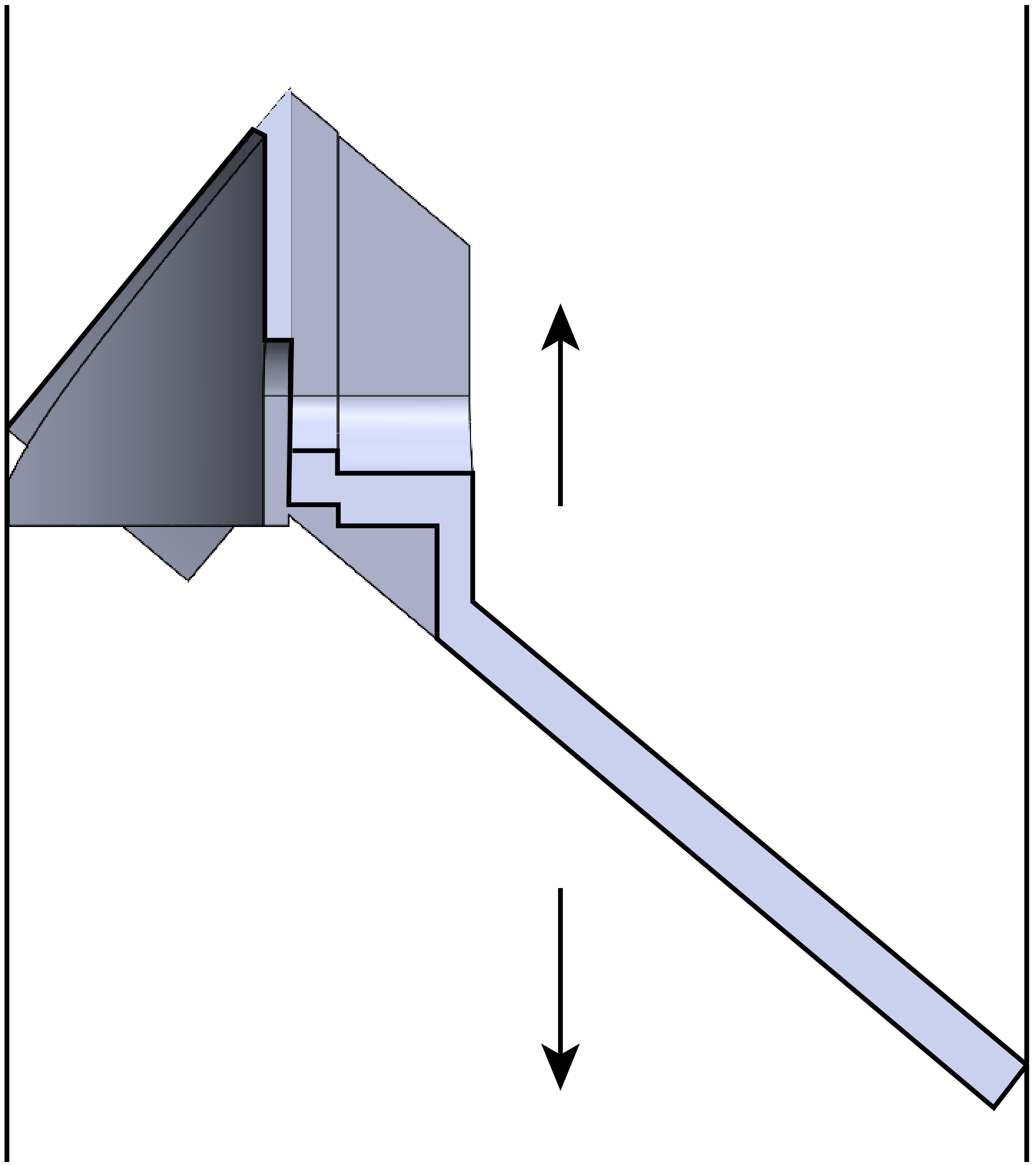


Figure 76: Due to the way the new top shell is designed, it can still be manufactured with the current mould set-up, which moves vertically from this view. The new design is annotated with the mould design layout.

To connect the top cover to the steam setter holder, two set screws are inserted in the holes originally meant for the snap fit to hook into. These screw into the two holes on the side of the steam setter holder. To connect the steam setter holder to the top shell, one set screw is inserted in the newly added holes in the top shell and screwed into steam setter holder (Figure 77).

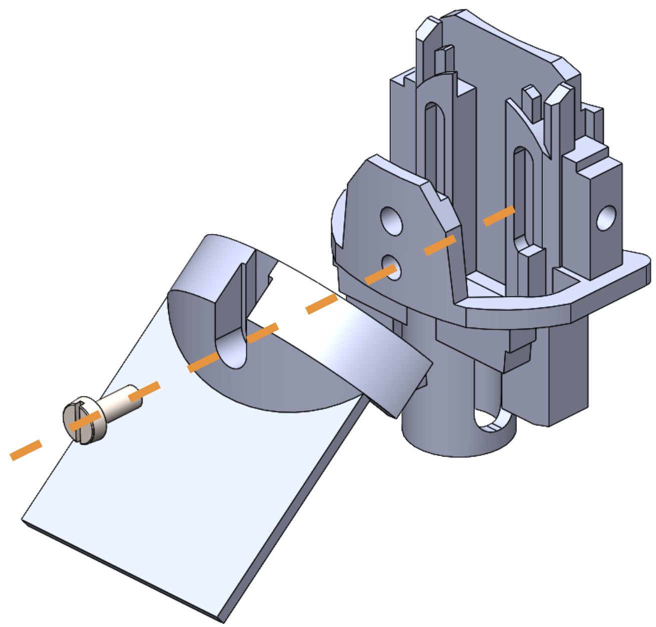


Figure 77: The new connection of the spare steam setter holder to the adjusted top shell.

7.2.5 | Concept assessment

The redesign of the steam setter holder and top shell, which replaces the snap fits with screw connections, was assessed in Table 16 based on the list of requirements from Table 15. The assessment of the redesign shows that it meets most requirements. The only requirement that was not met regards the disassembly with hand motion. Instead, the user needs a flathead screwdriver to remove the single screw that needs to be taken out to take the steam setting assembly out of the iron. All other requirements were met.

Table 16: Assessment of the snap fit redesigns based on the list of requirements. Green = meets requirement, yellow = possible issues in meeting the requirement, red = does not meet requirement.

Requirement category	Requirement	Redesign
Must have	The parts can be manufactured within the limitations of the current assembly method. All parts for this case study are plastic injection moulded parts.	
	The spare part can be manufactured within the limitations of SLA.	
	The user can set the steam function in three settings (functional equivalence).	
	The part and spare part are interchangeable.	
Should have	The steam setting assembly can be taken out with hand motion. This is because the user needs to remove the assembly monthly for cleaning (Tefal, 2024).	
	Disassembly and assembly can be repeated >50 times without compromising functionality. This is because the assembly needs to be removed monthly for cleaning (Tefal, 2024).	
	The part can be manufactured within the current mould designs (Appendix I), for viability.	
	No additional post-processing is required for the spare parts besides support removal, for the viability.	
Could have	No additional parts are added, for the viability of the product.	
	Parts that are not custom-IM parts are not changed, to limit the number of changes required to the product for viability.	
Won't have	No changes are made to the manufacturing method of the parts.	
	No changes are made to the current selection of off-the-shelf parts.	

7.3 | Conclusion of the snap fits redesign case study

The goal of this study was to see how the form factor optimisation guide could be used to redesign a complex part that is coupled to many parts, resulting in interchangeable, functionally equivalent parts produced with IM and SLA. Two snap fits in the steam setter holder were replaced for screw connections in the redesign.

Having a defined form factor to work with during ideation allowed the development of a concept that meets nine out of ten requirements. Without the defined form factor, it was hard to develop technically feasible concepts that did not undermine the functionality of the assembly. Determining the form factor was enabled by gradually mapping in the product architecture map which feature is included in the part for which reason, using the geometry-based part coupling approach. This resulted in fourteen functional surfaces (a-n in Figure 70 and Figure 71). Tackling the design problem from an OEM perspective also enabled this design, since the concept depends on the redesign of the top shell as well.

Discussion

This chapter reflects on the results of the research and discusses the recommendations for future research.

The form factor optimisation guide was developed using already existing products. The product architecture maps that were composed with the geometry-based part coupling approach use the Disassembly Map method to provide the positioning of the parts in the map. The Disassembly Map method is not meant to be used in the early stages of the design process (De Fazio et al., 2021). In the OEM design process, it may be more viable though to use the guide during the design process instead of reverse engineering the form factors for spare part production based on the fully designed product (Figure 78). To allow for this, the guide may need adjustments. It may be valuable to be able to note down which parts require a redesigned spare part and use the product architecture map as a 'living' document which is built up gradually during the design process. A design method that may be suitable to use alongside building the product architecture map is the Fish trap model by Muller (2001). This is because the method starts with a basic product structure that is developed into a material concept with defined parts through multiple iterations. A product architecture map could be developed by starting with the functions and entering components and their relations. To use the product architecture map as an overlay of information on top of the disassembly map, there needs to be an easy way to adjust the position of the parts once the disassembly map can be made. A valuable addition may also be the possibility of adding multiple design options in the product architecture map, similar to a product configuration scheme (Begelinger et al., 1999).

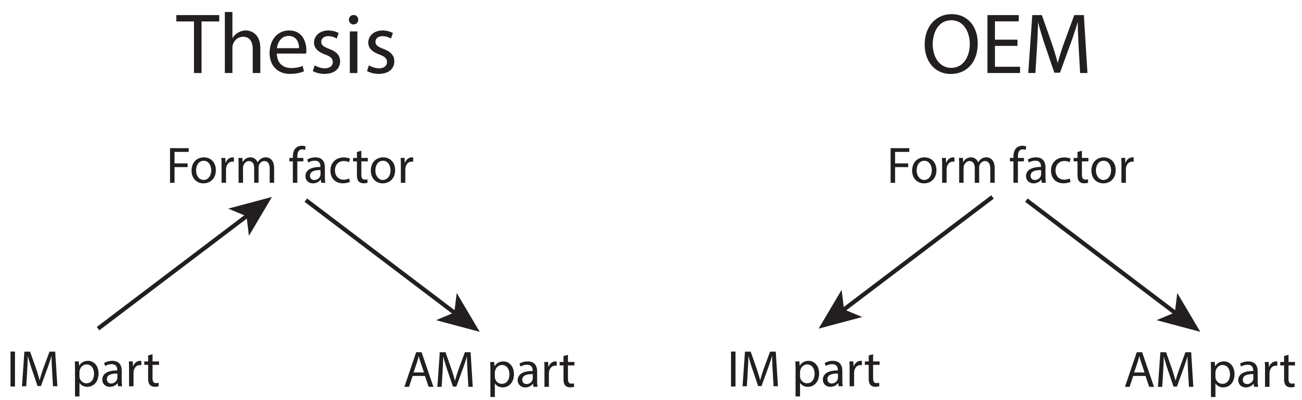


Figure 78: The form factor was derived from the IM part to design the AM part in the development in the approach (left), but in the OEM process it may be desired to use the form factor during the design process of both parts (right).

The form factor optimisation guide was developed using only three consumer electronic products and applied in two case studies. It has shown to be an effective guide in helping design interchangeable, functionally equivalent spare parts. The case study show design options that are possible within the existing form factor and that require changes to the design of coupled parts through reciprocity. However, judgements on the part feasibility regarding performance are limited by my design knowledge and available time for the redesigns. None of the designs achieved a Technology Readiness Level higher than level 3: *"Analytical and experimental critical function and/or characteristic proof of-concept"* (Mankins, 1995). Therefore, no judgements can be made on whether the spare parts could be certified and used for repair. Lack of standardisation complicates the certification process of AM spare parts (Pereira et al., 2019). Furthermore, it also takes time to compose the product architecture map and form factors. Application of the guide in an OEM-setting is required to evaluate how the guide influences the development time of spare parts. To increase the viability of the guide in the spare part design process, a solution could be to develop a list of solutions to troublesome features, such as the bayonet closure to replace the screw threads in Chapter 6. This way, designers can reuse spare part design solutions and reduce the development time needed to produce feasible, certified spare parts.

The form factor optimisation guide focuses on the geometrical design freedom to be able to produce spare parts. However, not all problems in spare part production are related to geometry, such as the need for multiple-materials or transparency (van Oudheusden et al., 2024). Chaudhuri et al. (2021) explore the suitability of spare part production with AM, mostly related to the complexity, requirements and materials of parts. Similarly, an evaluation of the applicability of the guide should be made to determine for which design problems the guide is most suitable and where the guide does not provide enough guidance.

The graphic representations of the geometry-based part coupling approach and form factor definition approach may need iterating. The approaches were not evaluated by other designers and therefore no conclusion can be made on how intuitive the approaches are for other designer's workflows. The form factor can be defined graphically in 2D reasonably well, depending on the complexity of the part. However, in 3D it becomes more complex, as shown in Figure 70. A solution could be to integrate the approach in CAD software, by allowing being able to assign functional surfaces to parts in an assembly, instead of having to annotate the model manually with colour. SolidWorks does have interference detection to indicate interferences between parts, but this is not optimal for this use case because for example parts coupled with a clearance fit do not pop up. Possibly, the form factor can be included in .3mf files, which is a file format that can contain more data regarding geometry to enhance the use of additive manufacturing for production purposes (3MF Consortium, 2025).

The application of the form factor optimisation guide is prone to inaccuracies caused by personal interpretations and human error. An example of personal interpretation is determining which parts have priority in the product architecture map. A solution for the correct application of the approaches in the guide when access to OEM data is available is to automate the approaches, for example in the CAD software. However, this automation was not explored.

Only SLA was considered for spare part production, with limited research conducted regarding the ability of SLS and FDM and no research on other AM technologies to produce spare parts. Because the steps in the guide can be applied regardless of the selected AM technology, the guide and the approaches within are expected to work for all AM technologies. The form factor is defined with a manufacturing driven strategy, coping with the limitations of the selected AM technology. However, the guide does not include a way to evaluate when to select which AM technology to optimise design space. Future research should investigate ways to expand the 'part optimisation' possibilities, by evaluating which AM technology is most suited to produce a part within the defined form factor.

The limitations of IM and SLA (Table 10) may be incomplete. Furthermore, SLA and the compatible materials are still developing (Formlabs, 2025b), so this table cannot be used as a complete overview of all limitations. For example, SLA was seemingly able to produce 1:1 copies of most IM parts, including all details. However, the 1:1 copy of the fine screw threads in the case study from Chapter 6 were not functionally equivalent with the original threads. It was therefore the combination of SLA's manufacturing limitations that posed an issue in the case study.

The developed part taxonomy, which was not needed for spare part production with SLA, should be evaluated and refined for other AM technologies with less geometrical freedom. This could help in identifying when these AM technologies are suitable for spare part production. Refinement can be done by choosing different parameters or threshold values, or by adding feature-based part recognition or context-based part recognition. Automated part recognition could also be a next step to improve how well the taxonomy can be incorporated in the design process. These refinements are shortly explored in Appendix D.

Conclusion

This research aimed to provide OEM designers guidance in designing their yet-to-be designed products that contain IM parts in a way that allows for interchangeable, functionally equivalent spare parts produced with AM. This research focused on SLA as the selected AM technology and the geometry and mechanical aspects of part design. The research resulted in a newly composed guide, referred to as the 'form factor optimisation guide' (Figure 79), that was used to design interchangeable, functionally equivalent parts with IM and SLA. This guide included two newly developed approaches: the geometry-based part coupling approach and form factor definition approach.

The geometry-based part coupling approach uses graphic representations in a product architecture map to indicate which parts are coupled and what the relationships are between the coupled parts that influence their geometry. The information of the relationships of coupled parts is used in the form factor definition approach, along with the list of requirements that is used to ensure the functionality of the part. In this approach, the design space and non-design space of a part (referred to as the 'form factor') are defined with functional volumes and functional surfaces, which result from the relationships of the coupled parts and the part's function. This is a manufacturing driven process. The determined form factor is used to optimise parts for production with IM and SLA that are interchangeable and functionally equivalent with a function-driven design strategy. It may occur that production of interchangeable, functionally equivalent parts is not possible or desired within the form factor due to the limitations of one of the technologies (Table 10). In this case, reciprocity between the designs of the coupled parts is required until a form factor is established that does allow for the production of interchangeable, functionally equivalent parts with IM and SLA.

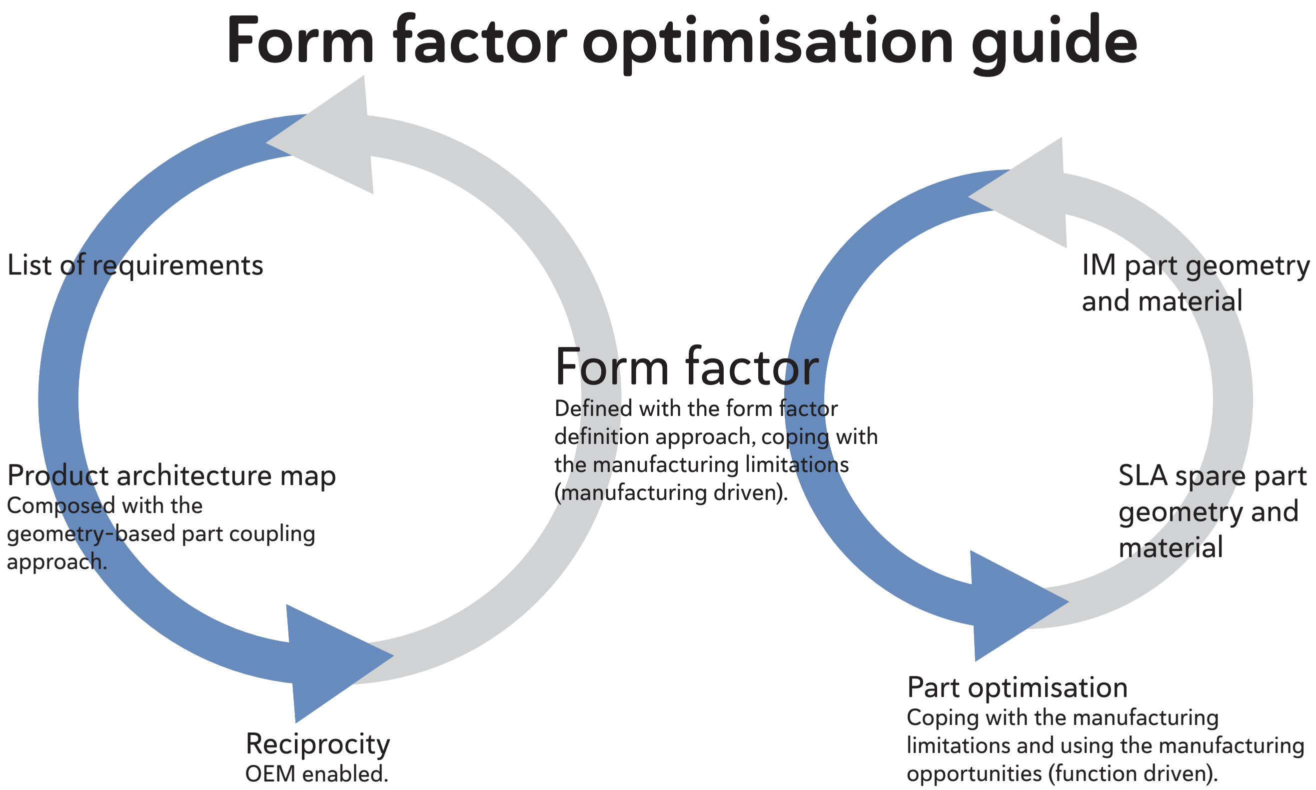


Figure 79: The newly developed form factor optimisation guide.

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Appendices

The following appendices are included:

A. Project brief
B. Manufacturing capabilities
C. Disassembly Tefal iron, Ferm cordless drill and Bosch hand blender
D. Taxonomy
E. Product architecture map development
F. Exploration of parametric part definition
G. Alternative design strategies
H. Case study pen
I. Case study snap fits

Appendix A | Project brief

Figure 80 shows the original project brief that was approved at the start of the project.

DESIGN FOR *our future*

TU Delft

Personal Project Brief – IDE Master Graduation Project

Name student W.H. Bakkeren **Student number** 4,841,921

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Manufacturing functionally equivalent spare parts using certified additive manufacturing methods to replace broken injection moulded parts

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

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

EU guidelines on `Right to Repair' require companies to provide spare parts over a prolonged period for common household products (European Parliament, 2024), for up to 10 years within 15 working days for several product categories (European Commission, 2019). Besides, there are various other guidelines and frameworks, such as: French repairability index, released in 2021 (*Indice de réparabilité*, 2024), replaced by a new sustainability index from 2025 onwards (*Indice de durabilité*, 2024) for various categories; Belgium framework law (Hellebaut, 2024); EU guidelines from 2025 for phones and tablets to provide spare parts and manuals for 7 years after the last distribution of the product (Ganapini, 2023).

Injection moulding (IM) is currently still one of the most used methods to mass-produce plastic parts. Once the mould has been made and the machine has been set up, parts can be produced quickly for a relatively low price per part, as long as the investment costs can be spread amongst many parts. It is thus mostly used for producing large batch sizes. Another manufacturing method, namely additive manufacturing (AM), like FDM, SLS, SLA, is mostly suited for small batch sizes due to the relatively large time it takes to produce the part.

Producing spare parts with additive manufacturing can be an interesting way for companies to avoid having to store many spare parts for years whilst still complying with the aforementioned guidelines. However, parts that are manufactured in one way (e.g. injection moulding) cannot always be copied 1:1 and manufactured in a different manner (e.g. additive manufacturing), because of the different manufacturing capabilities (Van Oudheusden et al., n.d. [unpublished manuscript]).

Current research on `Design for Repair' is mostly on product-level, limited to how to make a product repairable. For example, with the help of disassembly mapping (De Fazio et al., 2021) and hotspot mapping (Flipsen et al., 2020), which Bahlmann (2023) has combined into one tool. There are also tips such as the use of visible, standardised fasteners (Design Council, 2024). All of these assume spare part availability, but there is limited research on how to produce spare parts with alternative manufacturing methods, such as AM. Buijserd (2022) and Arriola (2022) have set up some guides that can help consumers in the production of spare parts, based on the original product. This graduation project will contribute to existing research by providing designers with guidelines on how to alter the original product to allow for 3D-printed spare parts in the future.

The first product that I will analyse during this graduation is a Tefal iron (Figure 1). Irons are commonly brought to repair café's (Postma, 2015). Furthermore, the product contains many features that are hard to implement in AM (Van Oudheusden et al., n.d. [unpublished manuscript]), such as multi-material, transparency, water resistance, strength and impact resistance. I will first focus on redesigning some mechanical parts of the iron with strength requirements, minding the shape, size and heat resistance requirements.

Figure 80: Project brief.

➔ *space available for images / figures on next page*

introduction (continued): space for images

image / figure 1 Tefal iron FV1711, the product that I will analyse first during this graduation project

image / figure 2

Figure 80 (continued).

Personal Project Brief – IDE Master Graduation Project

TUDelft

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

For some products, it is not possible to produce functionally equivalent spare parts using additive manufacturing that fit within the original product.

Problems in performance of a product can occur due to the properties of the manufacturing methods and materials that are used. Besides that, there are limitations to the changes that can be made to the original part to create the spare part, since it has to fit within the original product architecture.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Develop design guidelines to enable the production of functionally equivalent spare parts, originally made by injection moulding, using additive manufacturing.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

The main research questions for this graduation project are:
- What problems arise when reproducing injection moulded parts using additive manufacturing?
- What design guidelines can help overcome the differences in the manufacturing capabilities of IM and AM to allow for a functionally equivalent product?

Besides background literature research into the specifications of IM and AM, I will retain a `research-through-design' approach, in which I will start with conducting a case study on the Tefal iron (Figure 1), consisting of:
Control test product parts' performance, or (simplified) calculation, depending on part complexity; (Partial) disassembly map: how does the part fit within the architecture of the product? ; CAD modelling the IM parts to be repaired and relevant neighbouring parts. Also contact original manufacturer; Design and produce spare part using AM; Compare performance of spare part to original part, using the same set up as the control test

The insights gathered during this case study should allow me to set up design guidelines, look into further specifics of the manufacturing methods and materials and decide on new product parts to analyse and redesign using a similar case study as mentioned above.

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a ***kick-off meeting, mid-term evaluation meeting, green light meeting*** *and* ***graduation ceremony****. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	20 sept 2024
Mid-term evaluation	11 nov 2024
Green light meeting	20 jan 2025
Graduation ceremony	27 feb 2025

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:
Holidays planned in week 52, week 1, week 6.

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

As an IPD student with a passion for sustainability (especially repair), manufacturing methods and developing the details of a product's embodiment, this project ticks all boxes for me. However, I have not been able to truly combine all three passions into a project yet thus far in my career.

Besides the technical challenges that this project will offer, I want to learn how to work effectively on my own on a project for 100 days. This includes the planning, but especially also dealing with any unforeseen circumstances that might cause delay. Furthermore, I want to focus on documenting all findings and research from the very start.

Figure 80 (continued).

Appendix B | Manufacturing capabilities

Table 17 contains the data on the manufacturing capabilities of SLA, SLS and FDM for various design requirements, composed by van Oudheusden et al. (2024).

Table 17: The manufacturing capabilities of SLA, SLS and FDM by van Oudheusden et al. (2024): "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. ... 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."

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]
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]

Table 17 (continued).

Design Requirement	Injection Moulding (IM)	Stereo-Lithography (SLA)	Selective Laser Sintering (SLS)	Fused Deposition Modeling (FDM)
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]
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 17 (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]

Appendix C | Disassembly of Tefal iron, Ferm cordless drill and Bosch hand blender

Figure 81, Figure 82 and Figure 83 respectively show the Tefal iron, Ferm cordless drill and Bosch hand blender that were used for the case studies after disassembly.

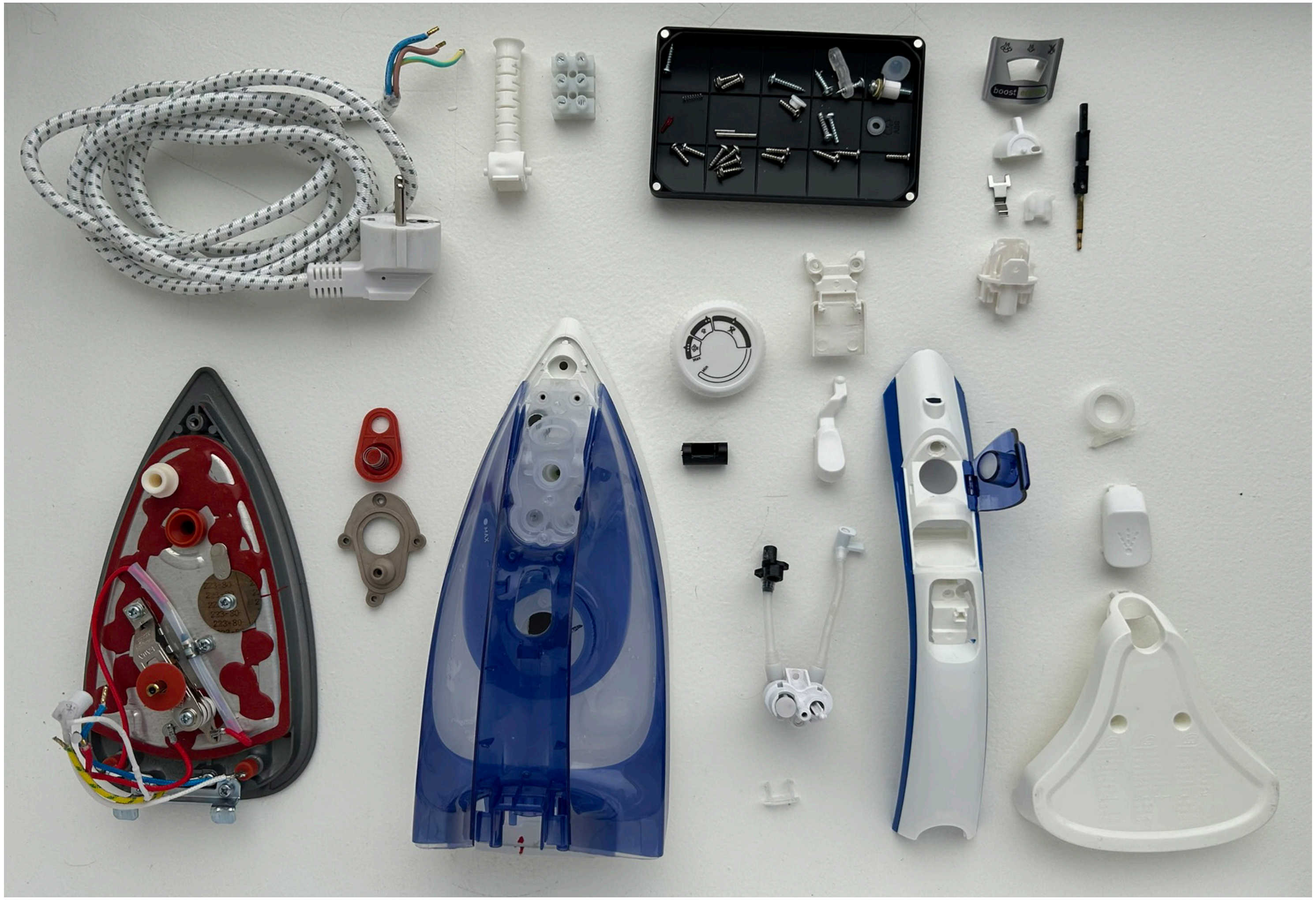


Figure 81: The Tefal iron FV1711 disassembled.

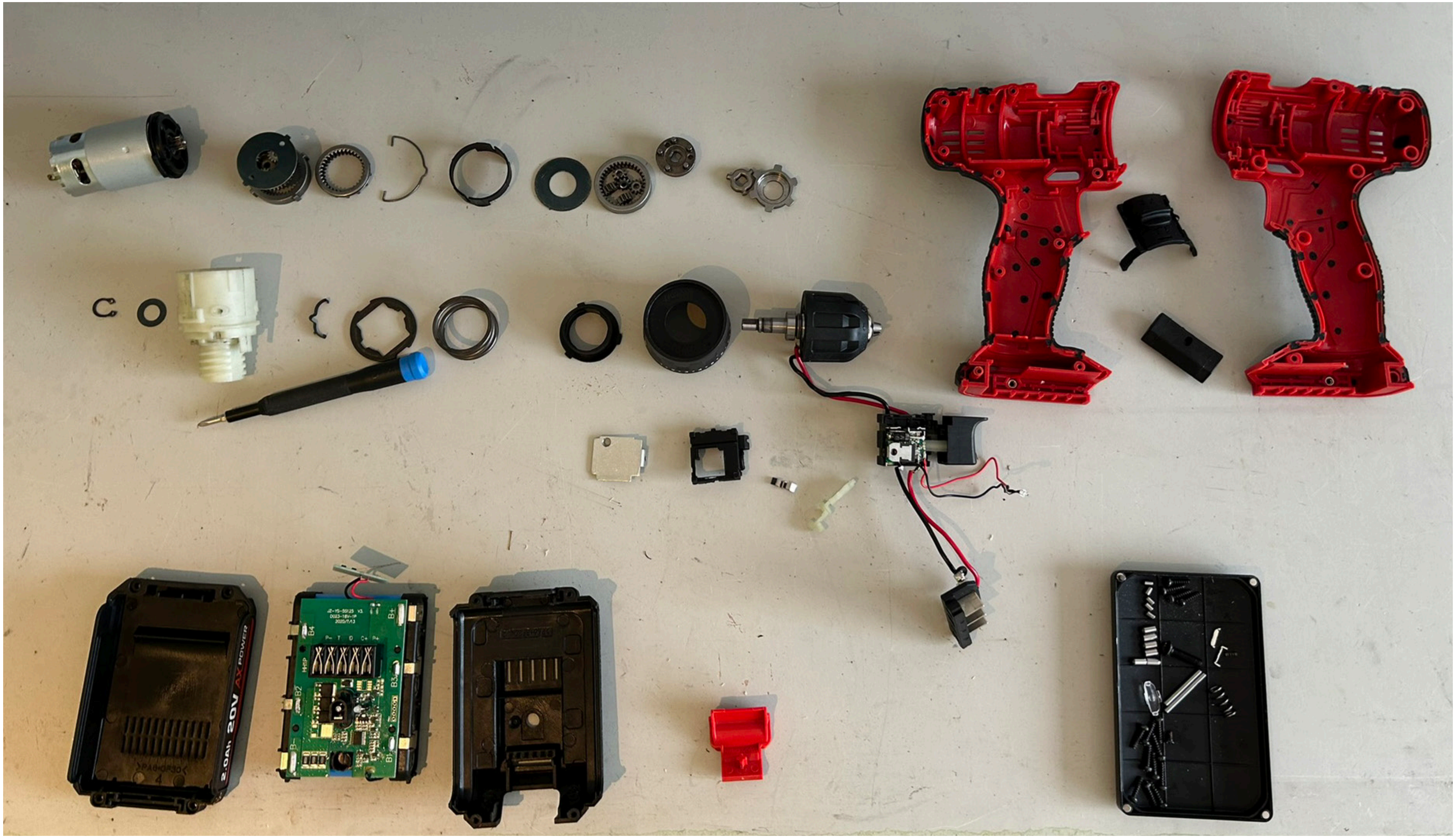


Figure 82: The Ferm cordless drill CDM1159 disassembled.

Figure 83: The Bosch hand blender ErgoMixx Style disassembled.

Appendix D | Taxonomy

AM and IM parts are manufactured in different ways. AM parts are manufactured in a one-directional movement from a build plate (Figure 84, left). IM parts are manufactured from different sides of a mould, connected at the parting line, which means that the part must have drafts in multiple directions (Figure 84, right). Anisotropy and the need for support material are manufacturing limitations that may occur in AM parts, depending on the AM technology (van Oudheusden et al., 2024).

A taxonomy of geometrical part structures was developed. Taxonomy is a term generally used to describe *"a system for naming and organising things, especially plants and animals, into groups that share similar qualities"* (Cambridge University Press & Assessment, 2024). This was done to explore if such a structured approach to part geometry would help in identifying complex part structures that pose limitations to production with AM. Having an accurate taxonomy could have multiple benefits for the production of spare parts:

- Chaudhuri et al. (2021) describe the need for a classification scheme to select spare parts that can be produced with AM.
- A taxonomy could help reuse spare part designs among similar parts. This would reduce the costs related to development and production, as indicated by Jian et al. (2021).
- It may be easier to get certification for parts that belong to the same part category. Certification of spare parts is currently an issue in the implementation of AM for spare part production (Opsomer, 2024).

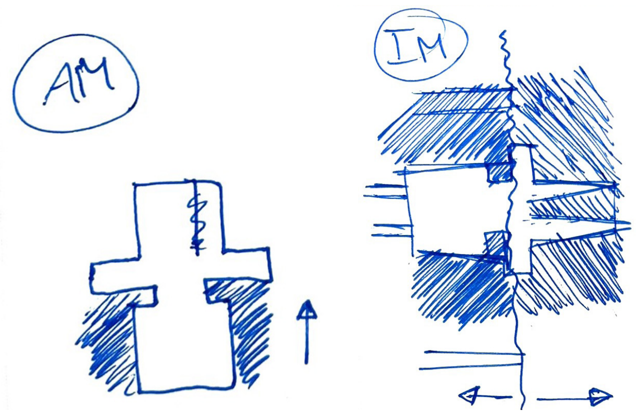


Figure 84: One-directional movement of AM (left) vs. the drafts in multiple directions of IM (right).

In this appendix, the following research question is answered:

"How can geometries of IM parts be distinguished in a taxonomy to identify complex part structures that could pose limitations to production in AM?"

This appendix is split up in several sections. The main appendix contains the method, results, discussion and conclusion. Appendix D.1 - D.4 show the additional information that was used to answer the research question.

Method for the taxonomy development

Existing IM parts were used as a starting point. First, seven knolled images of disassembled products were analysed visually and clustered instinctively into different categories, based on their shape. Six of the knolled images (Appendix D.1) were gathered from existing student projects. The knolled images were chosen randomly from a selection of available images of disassembled consumer electronics products. The seventh knolled image was made by disassembling a Tefal iron FV1711 (Appendix C).

Afterwards, literature was reviewed on existing taxonomies, to serve as inspiration on how these were developed and what parameters were used. The reviewed literature includes the following works:

- Middle et al. (1970) worked on *"an industrial classification scheme ... to use in bringing together workpieces (products) which are similar in shape, characteristic, size and material to enable rationalization, standardization and variety reduction to be carried out in the design and production planning functions."*
- Ovtcharova et al. (1992) provide a classification on feature-level.
- Zhang et. al (2012) present a concept to match certain design problems based on a 'design problem dimension' to theories and methodologies.
- Rucco et al. (2019) have implemented machine learning in classifying typical mechanical components.
- Volke et al. (2023) have worked on

recommending IM parameter settings using machine learning based on previous parts with the *"highest geometric similarity".*

Based on the literature and insights gathered from clustering part geometries in categories, a list of parameters was drafted that may distinguish between the various part geometry categories (Appendix D.2). Data was collected for some of the parameters, based on two criteria:

- It must be plausible that the parameter can **distinguish between the aforementioned part clusters**. For example, a parameter such as 'number of features' is more likely to distinguish between a simpler and more complex structure than 'material', since the material mostly does not influence the geometric complexity.
- The parameter must be **measurable within the means and timeframe** that is set for this research. For example, the mass of a part is easy to measure with a scale, whereas the total surface area of the part is very hard and time consuming to measure without access to its CAD file.

To determine which parameters can distinguish part categories, data was gathered from three consumer electronics products (Appendix D.3). These were disassembled so the data for each part could be collected. The chosen products are a Tefal iron FV1711, a Ferm cordless drill and a Bosch hand blender (Appendix C). These consumer electronics products were chosen because they contain several parts with geometrical and mechanical requirements.

An important note regarding this research is that this approach is different compared to the OEM perspective. To collect the data present in Appendix D.3, the data was reverse-engineered based on the single available parts, whereas an OEM could extract the data from a digital CAD model. Some notes on the data collection process:

- **Dimensions:** These were measured with digital callipers with a resolution of 0.01 mm. Measurements larger than 150 mm or lacking parallel surfaces narrow enough to measure with the callipers were measured with a try square or tape measure with a resolution of 1 mm.
- **Volume:** The volume of the parts was measured on the Hildebrand Densimeter Model H-300S (with a resolution of 0.001 cm^3) for all parts that fit within the machine (at a maximum size of 149x102x48 mm). The volume for the larger parts that did not fit was calculated by multiplying the weight with the density. The density was looked up in the Granta EduPack 2024 R2 software, after determining the material of the parts via the material annotations on the part. The weight of these parts was measured on the ABT 320-4M scale, with a resolution of 0.1 mg.

The gathered data for the Tefal iron FV1711 was plotted on graphs with various parameters on the axes (Appendix D.4). With each instinctive category colour coded, it was visually determined whether the parameter was distinctive in separating part geometry categories or not. Furthermore, the 'threshold value' was determined, which is the absolute value that separates categories. An example of a threshold value could be: if the height of the part is bigger than its width, it falls in category A; if it is smaller it falls in category B. The parameters and threshold values were adjusted based on the data of the Ferm cordless drill and Bosch hand blender.

These parameters and their threshold values were put into a flowchart, using as many parameters as required to distinguish between all the instinctive categories. Important to note here is that there is no judgement on the manufacturability of each of these categories.

Results of the taxonomy development

The visual inspection of ten consumer electronics products (Appendix C and D.1) yielded several part categories, which were clustered into six categories:

- **'Clamshell':** Relatively flat hollow structures, with features mostly protruding up from one plane. For example, the back cover of the Tefal iron FV1711 (Figure 85A).
- **'Midplaner':** Double-sided hollow structure, with features mostly protruding up and down from one plane. For example, the PCB cover of the Ferm cordless drill (Figure 85B).
- **'Complex chaos':** Complex 3D structures with features on many sides of the part. For example, the steam setter holder of the Tefal iron FV1711 (Figure 85C).
- **'Tubes':** Cylindrical parts with a through-hole. For example, the cord connector from the Bosch hand blender (Figure 85D).
- **'Quirky cylinder':** Mostly cylindrical parts with some additional features. For example, the pump shafts from the Tefal iron FV1711 (Figure 85E).
- **'Pancakes':** Parts that are thin and wide, like gaskets, washers and rings. For example, the O-ring from the Tefal iron FV1711 (Figure 85F).

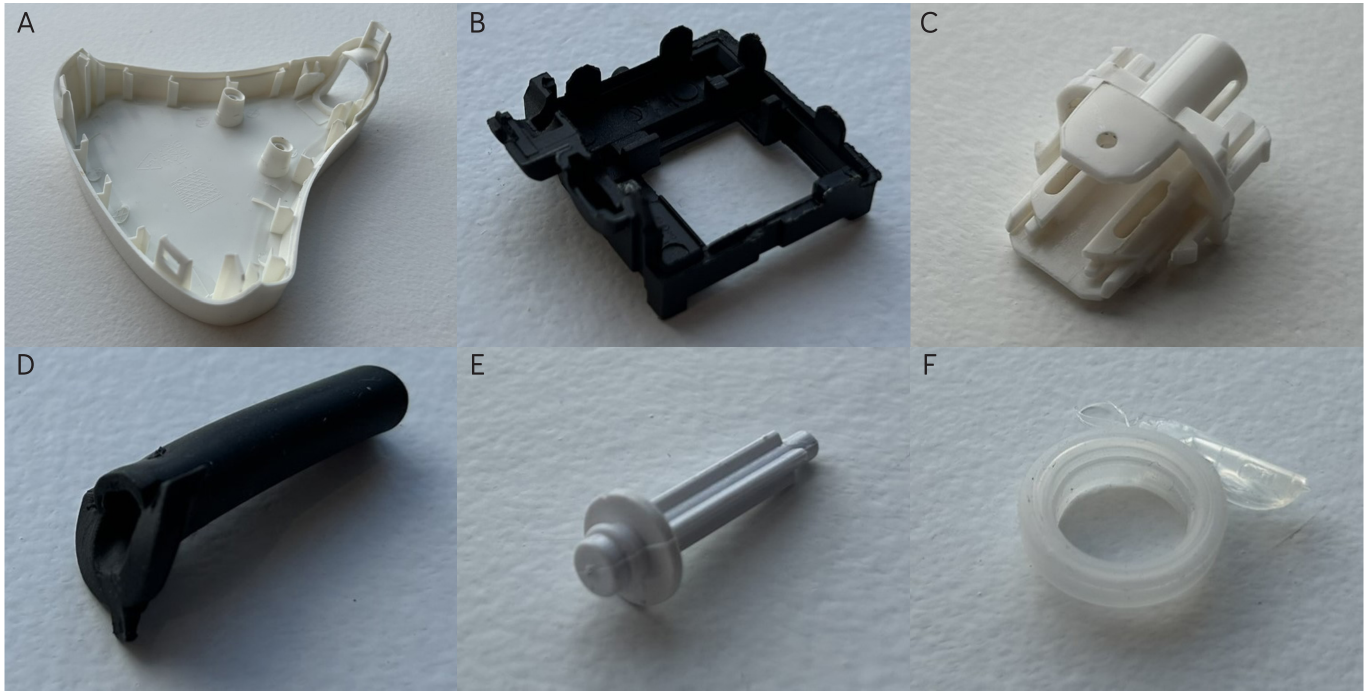


Figure 85: Examples for each of the 6 instinctive part categories.

The parameters that ended up being distinguishing between the various categories of part geometries are the following:

- **V_part / V_MBB:** The volume of the part (V_part) divided by the volume of the minimum bounding box (V_MBB) of the part. This results in the percentage of the minimum bounding box filled with material. The minimum bounding box also used in a taxonomy by Rucco et al. (2019) and is calculated by multiplying the outer dimensions of the part (Figure 86).
- **Visible sides:** the number of sides of the part visible to the user during regular use.
- **Feature directions:** defined as 'the number of directions in which the part has draft angles', always resulting in 2-6 directions. In cases where a feature goes from one side of the product to the other, it is counted as two directions, even if it could be moulded with just a single pin moving in one direction.
- **Mould pulling direction:** This compares the primary usage direction of the part compared to the mould pulling direction. The options for this are 'axial' and 'lateral', with axial being in line with the primary usage direction of the part, and lateral being perpendicular to the primary usage direction (Figure 87). Lateral is mostly the case for shapes that are roughly cylindrical but are not moulded in the direction of the rotational axis of the part.
- **h_MBB / w_MBB:** The height of the minimum bounding box divided by the width of the minimum bounding box, to distinguish

between tall and short shapes. This parameter is also used by Rucco et al. (2019).

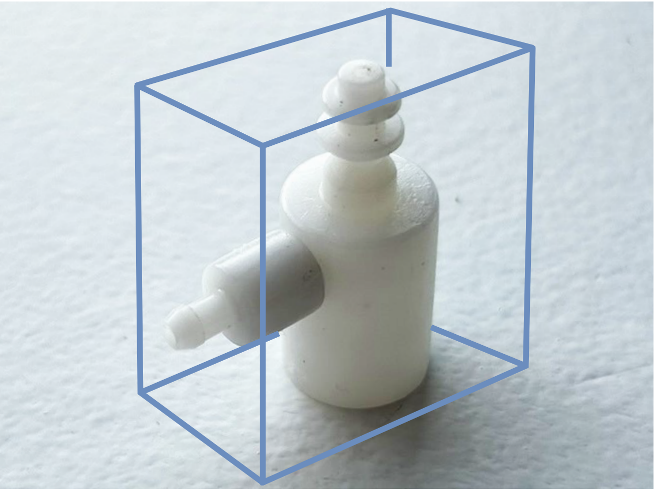


Figure 86: The minimum bounding box visualised.

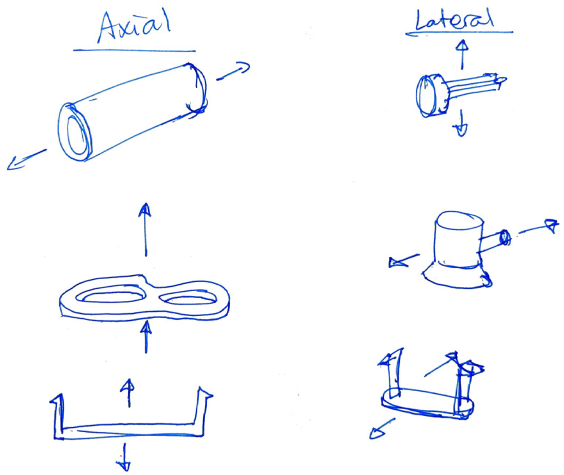


Figure 87: Examples of axial and lateral mould pulling directions of parts of the Tefal iron FV1711.

The parameters and part geometry categories are plotted in Figure 88. By inserting the flowchart as a formula in the datasheet, the expected categorisation could be tested against the flowchart's categorisation. This yields a total of 46 out of 59 IM parts that were categorised in the same part category as where they were put intuitively, as shown in Appendix D.3, meaning that thirteen were not. This may be due to mistakes in the intuitive classification, or that the taxonomy is inaccurate.

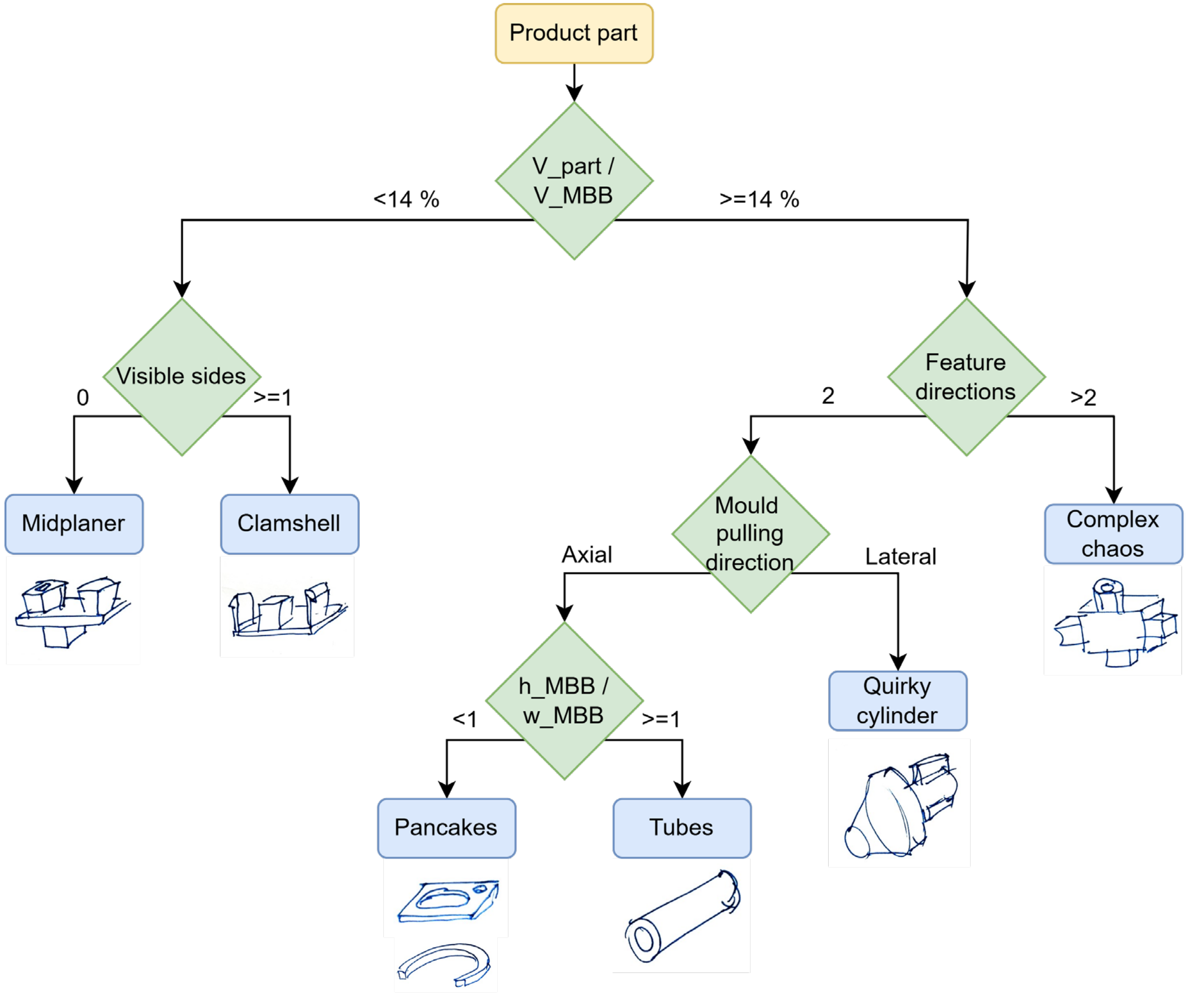


Figure 88: Flowchart for IM part taxonomy.

Discussion of the taxonomy development

The taxonomy can be refined. Bonino et al. (2023), Rucco et al. (2019) and Lupinetti et al. (2017) suggest the use of context-based recognition and feature recognition to improve the accuracy of taxonomies in their work. This involves checking which parts directly and indirectly interact with each other, the overlap of the parts' minimum bounding boxes and defining features that determine a part's category. However, because the taxonomy was deemed not needed for SLA spare parts since SLA could produce the complex part structure of the steam setter holder, refinements of the taxonomy were not further explored.

Conclusion of the taxonomy development

The goal of this appendix was to find out how geometries of IM parts could be distinguished in a taxonomy to identify complex part structures that could pose limitations to production with AM. A taxonomy with the following defining parameters was composed:

- V_part / V_MBB
- Visible sides
- Feature directions
- Mould pulling direction
- h_MBB / w_MBB

There were 13 differences between the 59 instinctive classifications and parametric classifications. This shows that refinement of the taxonomy is possible but this was not further explored.

Appendix D.1 | Knolled images

Figure 89, Figure 90, Figure 91, Figure 92, Figure 93 and Figure 94 served as inspiration for different categories of parts for the IM part taxonomy.

Figure 89: Knolled image of an airfryer (Bakkeren et al., 2023).

Figure 90: Knolled image of a vacuum cleaner (Buijserd, 2022).

Figure 91: Knolled image of a keyboard, headphones, webcam and mouse (Bahlmann, 2023).

Figure 92: Knolled image of a table fan (Bahlmann, 2023).

Figure 93: Knolled image of a computer mouse (Bahlmann, 2023).

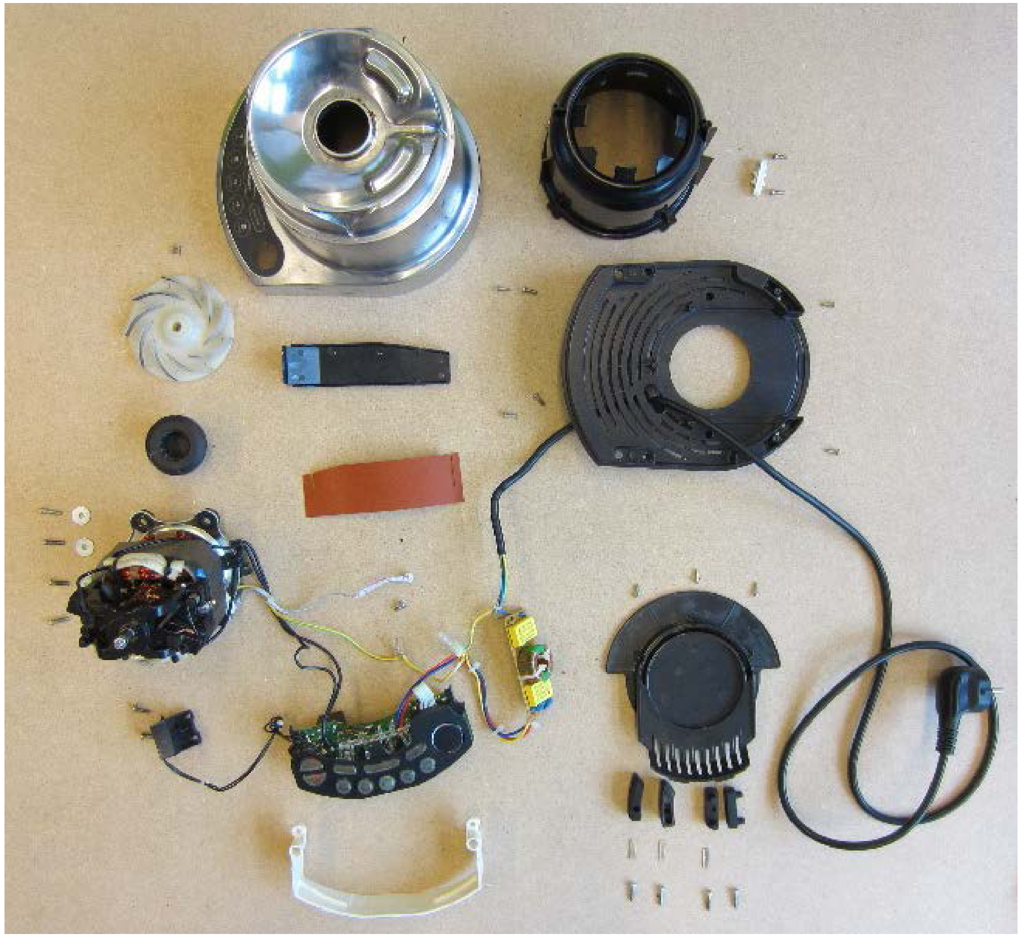


Figure 94: Knolled image of a coffee machine (Flipsen et al., 2020).

Appendix D.2 | Possible parameters

The following parameters were considered for the taxonomy:

- Thinnest wall thickness (mm)
- Thickest wall thickness (mm)
- Average wall thickness (mm)
- Outer dimension X (mm)
- Outer dimension Y (mm)
- Outer dimension Z (mm)
- Weight (g)
- Material
- Density (g /cm^3)
- E-modulus (GPa)
- Material volume
- Build volume (mm^3)
- Average wall thickness / build volume (mm^-2)
- material volume / build volume (%)
- Part of mechanism (y/n)
- Forces on part
- Other requirements
- Fastener directions
- Amount of fasteners
- Visible, must be aesthetic, sides
- Amount of ribs
- Amount of features
- Feature directions
- Smallest feature size (mm)
- Redesign expected (y/n)
- SLA-printable (yes, likely, unlikely, no)
- SLS-printable (yes, likely, unlikely, no)
- FDM-printable (yes, likely, unlikely, no)
- Mould pulling direction

Appendix D.3 | Part data

Table 18 contains all data of the IM parts of the Tefal iron, Bosch hand blender and Ferm cordless drill for the used parameters in the taxonomy.

Table 18: All used parameters filled in for the IM parts of the Tefal iron, Bosch hand blender and Ferm cordless drill. The densities marked in orange are estimates based on the mix of materials, because there was no data available on the specific mix.

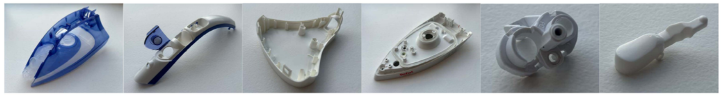
Photo	**Elaboration**						
Expected category	Clamshell, Complex chaos, button, Pancake, tube, pancake	Midplaner	Clamshell	Clamshell	Clamshell	Midplaner	Clamshell
Category after flowchart	Sorted by type after using taxonomy flowchart	Clamshell	Clamshell	Clamshell	Clamshell	Midplaner	Clamshell
Product		Tefal iron	Tefal iron	Tefal iron	Tefal iron	Tefal iron	Tefal iron
Outer dimension X (mm)	Largest dimension in X direction	211	227	112.3	253	31.15	49.84
Outer dimension Y (mm)	Largest dimension in Y direction	113	40	113	113.6	22.5	16.85
Outer dimension Z (mm)	Largest dimension in Z direction	89	50	30.3	49.6	31.9	18.35
Weight (g)	Weight of the part (IM only)	98.563	25.390	22.3435	137.902	2.48	1.8
Material	What the part is made of, e.g. PC, PP. Only written down if it is indicated on the part	PP	PP	PP	PBT	PC	PC
Density (g /cm^3)	From Granta EduPack 2024 R2 software	0.902	0.902	0.902	1.34		
Density (g / cm^3)	Measured on Densimeter Hildebrand H-300S release 1.0					1.144	1.201
Material volume (weight / density) (cm^3)	Volume calculated with weight and density	109.3	28.1	24.8	102.9		
Material volume measured (cm^3)	Volume measured using density meter					2.166	1.501
Minimum bounding box (MBB) volume (mm^3)	outer dimension x * outer dimension y * outer dimension z	2122027	454000	384504	1425544	22357.91	15410.4
material volume / MBB volume (%)	What is the 'infill' of the product?	5.1	6.2	6.4	7.2	9.7	9.7
Visible sides	The number of sides of the part visible to the consumer during regular use.	2	5	5	4	0	5
Feature directions	The number of directions in which the injection mould would have needed to move in order to create the part	6	3	4	2	2	4
Mould pulling direction	The primary usage direction of the part compared to the mould pulling direction	Axial	Axial	Axial	Axial	Axial	Axial

Table 18 (continued).

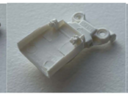
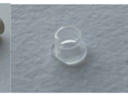
Photo														
Expected category	Midplaner	Midplaner	Clamshell	Midplaner	Clamshell	Clamshell	Clamshell	Midplaner	Quirky cyli	Complex c	Complex c	Tube	Tube	Complex c
Category after flowchart	Midplaner	Midplaner	Clamshell	Midplaner	Clamshell	Clamshell	Clamshell	Midplaner	Quirky cyli	Complex c	Complex c	Complex c	Pancake	Complex c
Product	Tefal iron	Tefal iron	Tefal iron	Tefal iron	Tefal iron	Tefal iron	Tefal iron	Tefal iron	Tefal iron	Tefal iron	Tefal iron	Tefal iron	Tefal iron	Tefal iron
Outer dimension X (mm)	55.65	48.1	31.2	19.22	28.6	46.15	23.83	36.85	10.22	27.72	34.86	71.16	7.45	14
Outer dimension Y (mm)	41.95	25.96	22.18	17.1	33	46.15	20.2	22.4	9.96	14.05	26.1	23	6.7	12
Outer dimension Z (mm)	13.5	24.34	27.3	23.1	19.65	15.3	9.82	11.2	28.84	32.14	17.68	19.2	4.94	14.3
Weight (g)	5.57	4.06	2.41	1.25	2.5	4.92	0.68	1.42	0.51	2.45	2.85	5.76	0.04	0.47
Material		PC	PC+ABS	PA	PC		PC				PC			
Density (g /cm^3)											1.2		0.9	
Density (g / cm^3)	1.628	1.197	1.038	1.376	1.111	1.206	1.089	1.157	1.211	1.349	1.178	1.201		1.029
Material volume (weight / density) (cm^3)													0.044	
Material volume measured (cm^3)	3.421	3.411	2.319	0.910	2.251	4.081	0.623	1.228	0.418	1.818	2.421	4.795		0.458
Minimum bounding box (MBB) volume (mm^3)	31515.99	30392.77	18892.04	7592.092	18545.67	32586.28	4727.014	9244.928	2935.658	12517.44	16086.1	31424.26	246.5801	2402.4
material volume / MBB volume (%)	10.9	11.2	12.3	12.0	12.1	12.5	13.2	13.3	14.2	14.5	15.1	15.3	18.0	19.1
Visible sides	0	0	5	0	3	5	3	0	0	0	0	6	0	0
Feature directions	2	3	2	2	2	4	4	4	2	5	6	4	2	5
Mould pulling direction	Axial	Axial	Axial	Axial	Axial	Axial	Lateral	Axial	Lateral	Lateral	Axial	Lateral	Axial	Lateral

Table 18 (continued).

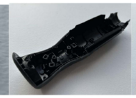
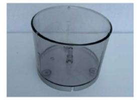
Photo													
Expected category	Complex c	Clamshell	Pancake	Tube	Quirky cyli	Complex c	Quirky cyli	Tube	Quirky cyli	Clamshell	Clamshell	Clamshell	Clamshell
Category after flowchart	Complex c	Complex c	Pancake	Tube	Quirky cyli	Complex c	Quirky cyli	Complex c	Pancake	Clamshell	Clamshell	Clamshell	Clamshell
Product	Tefal iron	Tefal iron	Tefal iron	Tefal iron	Tefal iron	Tefal iron	Tefal iron	Tefal iron	Tefal iron	Bosch hand	Bosch hand	Bosch hand	Bosch hand
Outer dimension X (mm)	10.06	8.27	22	8	41.33	12.45	8.85	10.93	11.4	207	203	102.91	121.12
Outer dimension Y (mm)	15.45	16.82	22	8	10.18	14.72	8.85	10.84	11.4	57.18	57.59	102.64	121.49
Outer dimension Z (mm)	10.95	10.7	6.8	8.8	6.05	7.53	16	21.56	6.5	56.43	40.45	154	93.69
Weight (g)	0.36	0.38	0.92	0.2	1.08	0.61	0.64	1.31	0.41	54.253	45.4111	117.258	110.741
Material										TPE+PP	TPE+PP	SAN	SAN
Density (g /cm^3)										1	1	1.07	1.07
Density (g / cm^3)	1.095	1.179	1.119	1.109	1.29	1.192	1.357	1.321	1.188				
Material volume (weight / density) (cm^3)										54.253	45.411	109.587	103.496
Material volume measured (cm^3)	0.325	0.318	0.824	0.182	0.840	0.511	0.474	0.991	0.343				
Minimum bounding box (MBB) volume (mm^3)	1701.926	1488.385	3291.2	563.2	2545.473	1379.978	1253.16	2554.455	844.74	667920.2	472891.6	1626653.1	1378636.1
material volume / MBB volume (%)	19.1	21.4	25.0	32.3	33.0	37.0	37.8	38.8	40.6	8.1	9.6	6.7	7.5
Visible sides	0	1	0	0	0	0	0	0	0	4	3	6	6
Feature directions	3	3	2	2	2	5	2	3	2	3	2	4	6
Mould pulling direction	Lateral	Lateral	Axial	Axial	Lateral	Axial	Lateral	Axial	Axial	Axial	Axial	Lateral	Axial

Table 18 (continued).

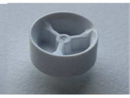
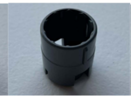
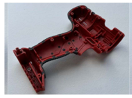
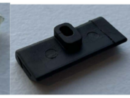
Photo													
Expected category	Clamshell	Complex cl	Complex cl	Tube	Pancake	Pancake	Pancake	Clamshell	Tube	Pancake	Clamshell	Clamshell	Clamshell
Category after flowchart	Clamshell	Clamshell	Complex cl	Tube	Pancake	Pancake	Clamshell	Clamshell	Tube	Pancake	Clamshell	Clamshell	Clamshell
Product	Bosch hand	Bosch han	Bosch han	Bosch han	Bosch han	Bosch han	Bosch han	Bosch han	Bosch han	Bosch han	Bosch han	Bosch han	Bosch han
Outer dimension X (mm)	121.19	51.73	34.33	31.07	29.36	30	53.14	41.8	13.21	17.81	24.84	76.34	118.9
Outer dimension Y (mm)	121.04	52.27	34.26	29.48	29.36	30	33.5	41.8	16.07	17.81	19.62	23.04	118.73
Outer dimension Z (mm)	76.77	42.33	21.8	35.37	18.21	19.26	18.46	34.07	35.08	12.07	26.52	15.31	23.14
Weight (g)	42.524	8.05	10.79	8.78	5.63	5.62	4.2	5.75	1.69	1	1.96	3.81	32.681
Material	PP							ABS					PP
Density (g /cm^3)	0.9												0.9
Density (g / cm^3)		1.229	1.403	1.213	1.391	1.343	1.415	1.046	1.207	1.149	1.408	1.189	
Material volume (weight / density) (cm^3)	47.249												36.312
Material volume measured (cm^3)		6.557	7.693	7.235	4.043	4.186	2.965	5.49	1.401	0.871	1.397	3.201	
Minimum bounding box (MBB) volume (mm^3)	1126126.7	114457.2	25639.98	32396.93	15697.19	17334	32862.31	59528.47	7446.947	3828.557	12924.81	26928.35	326667.3
material volume / MBB volume (%)	4.2	5.7	30.0	22.3	25.8	24.1	9.0	9.2	18.8	22.8	10.8	11.9	11.1
Visible sides	5	5	5	0	0	0	2	5	5	6	1	5	5
Feature directions	6	6	6	2	2	2	2	4	2	2	2	2	6
Mould pulling direction	Axial	Axial	Axial	Axial	Axial	Axial	Axial	Axial	Axial	Axial	Axial	Axial	Axial

Table 18 (continued).

Photo													
Expected category	Clamshell	Clamshell	Complex cl	Clamshell	Pancake	Clamshell	Clamshell	Pancake	Midplaner	Midplaner	Misc / Pan	Clamshell	Clamshell
Category after flowchart	Clamshell	Clamshell	Complex cl	Pancake	Midplaner	Clamshell	Clamshell	Pancake	Midplaner	Pancake	Pancake	Pancake	Clamshell
Product	Ferm cordl	Ferm cordl	Ferm cordl	Ferm cordl	Ferm cordl	Ferm cordl	Ferm cordl	Ferm cordl	Ferm cordl	Ferm cordl	Ferm cordl	Ferm cordl	Ferm cordl
Outer dimension X (mm)	187	187	42.08	51.42	36.05	33.03	44.46	36.14	33.64	37.32	41.95	117.04	116.64
Outer dimension Y (mm)	116.82	116.85	44.38	51.15	35.55	28.46	36.58	34.77	30.26	7.97	19.27	78.88	78.68
Outer dimension Z (mm)	41.8	31.94	62.84	36.08	12.45	32.81	27	13.23	14.74	12.49	10.14	24.76	32.1
Weight (g)	103.391	102.118	27.2	31.03	1.39	5.96	5.24	3.55	2.56	0.86	6.21	49.16	45.64
Material	PA6+GF30-	PA6+GF30-TPE		PA6+GF30		PA6+GF30	PA6+GF30	PA6+GF30				PA6+GF30	
Density (g /cm^3)	1.3	1.3											
Density (g / cm^3)			1.649	1.36	1.383	1.433	1.385	1.45	1.496	1.373	1.396	1.396	1.378
Material volume (weight / density) (cm^3)	79.532	78.552											
Material volume measured (cm^3)			16.499	22.811	1.005	4.157	3.782	2.45	1.709	0.628	4.45	35.207	33.124
Minimum bounding box (MBB) volume (mm^3)	913135.2	697919.3	117354.4	94895.2	15955.64	30842.51	43911.36	16624.66	15004.53	3715.031	8196.938	228587.2	294589.2
material volume / MBB volume (%)	8.7	11.3	14.1	24.0	6.3	13.5	8.6	14.7	11.4	16.9	54.3	15.4	11.2
Visible sides	4	4	0	4	0	4	1	0	0	0	6	5	5
Feature directions	2	2	4	2	2	2	2	2	2	2	2	2	2
Mould pulling direction	Axial	Axial	Lateral	Axial	Axial	Axial	Axial	Axial	Axial	Axial	Axial	Axial	Axial

Appendix D.4 | Graphs

Graphs were made to provide some insights in the quantification of the instinctive classification of the parts. Having placed all parts of the Tefal iron in categories before collecting the quantitative data, gives an indication of how well the assumptions match the parametric classification.

Mass vs. Material volume / build volume

Plotting mass against material volume / build volume in Figure 95 and Figure 96 shows that there is a rough distinction at +- 14 % infill, distinguishing between 'clamshells' and 'midplaners' and the other categories. As expected, the first two have relatively low infill due to the space between the features. The 'complex chaos' category is quite solid.

The expectation is that for larger tubes, as the diameter grows, the wall thickness will be relatively thinner and thus those parts will be placed more near the bottom of the graph.

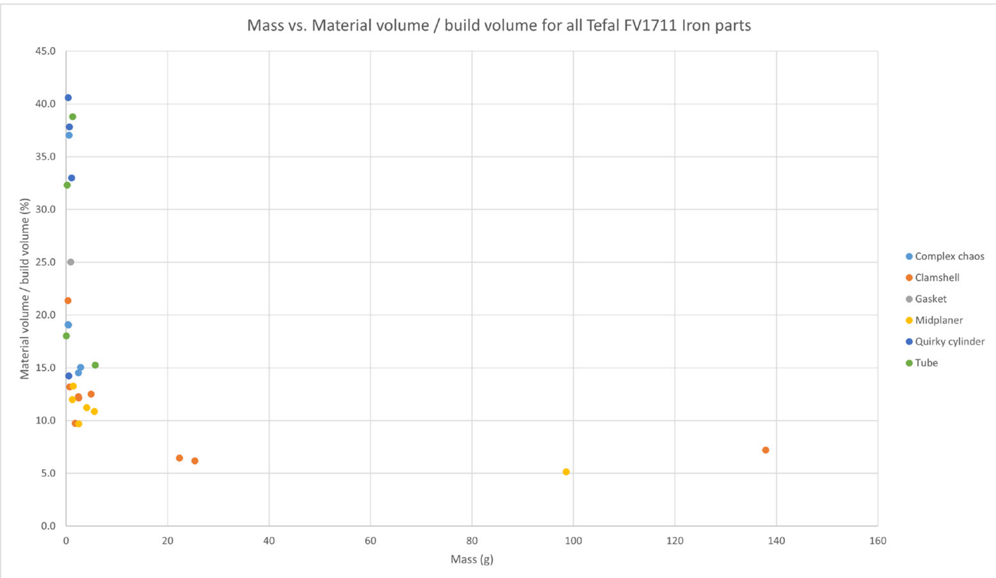


Figure 95: Mass vs. Material volume / build volume for all parts of the Tefal iron FV1711.

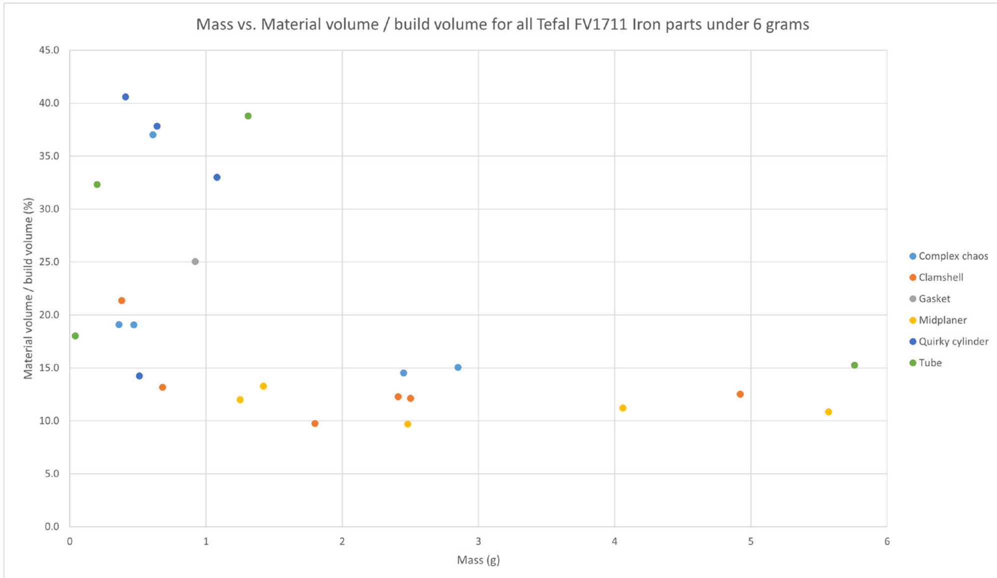


Figure 96: Mass vs. Material volume / build volume for all parts of the Tefal iron FV1711 under 6 grams.

Feature directions vs. Material volume / build volume

Putting feature directions on the X-axis (Figure 97) shows that all clamshells have two to four feature directions and all quirky cylinders just two. The complex chaos category has mostly five.

Visible sides vs. Material volume / build volume

Putting visible sides on one of the axes of the graph gives a clear distinction between clamshells and the rest of the categories (Figure 98). One outlier here is one of the tubes (cord holder).

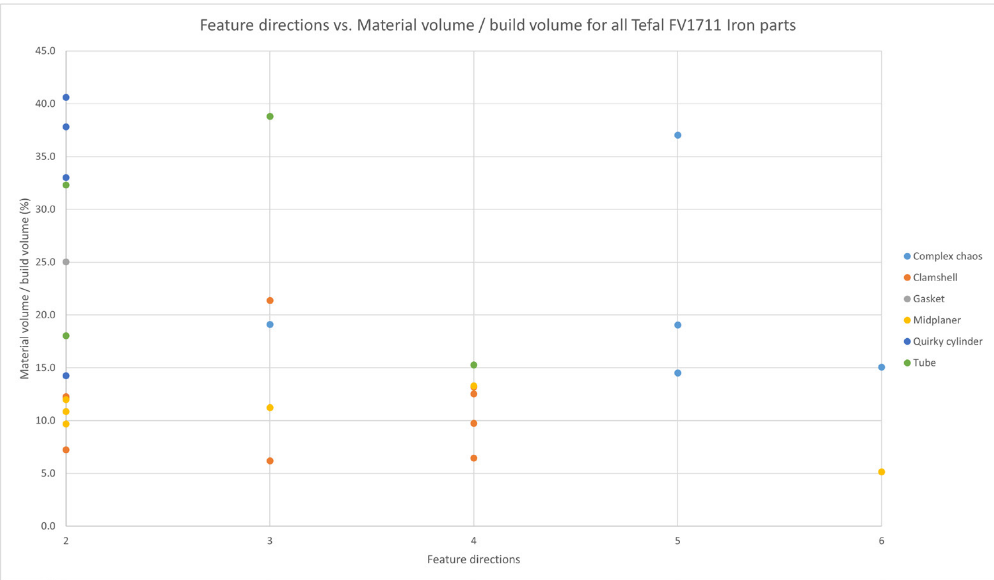


Figure 97: Feature directions vs. Material volume / build volume for all parts of the Tefal iron FV1711.

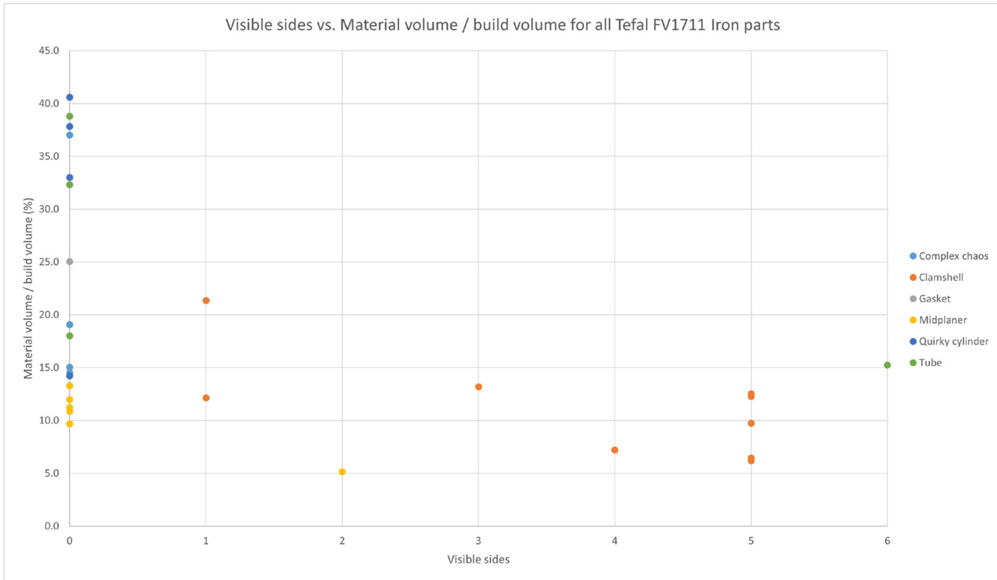


Figure 98: Visible sides vs. Material volume / build volume for all parts of the Tefal iron FV1711.

Appendix E | Product architecture map development

Figure 99 shows the first version of the product architecture map of the Ferm cordless drill. In essence, the shape and placement of the parts almost looks like the drill. The map is very cluttered though, with many lines that pass each other. What is unclear at this point is what defines whether parts influence each other's geometry and if wire management and electrical connections should be incorporated.

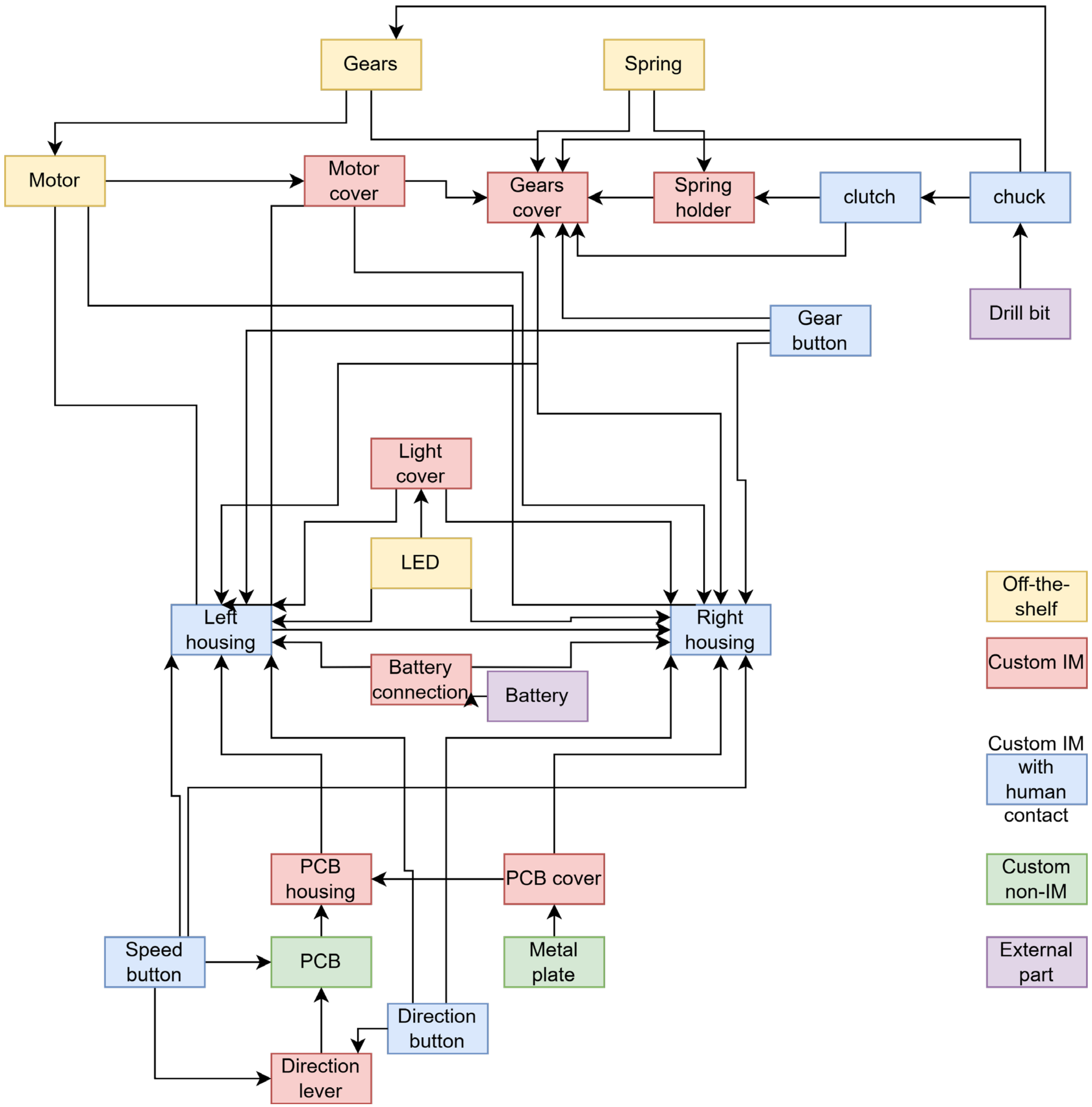


Figure 99: Product architecture map of the Ferm cordless drill, version 1.

In the next version (Figure 100), the following changes were made:

- The left and right housing combined into 'outer housing'.
- The parts rearranged to roughly match their location in the drill.
- Neater linework.
- Addition of a part category.

The diagram shows four subassemblies with the following purpose: rotation, lighting, control, power (top down), which are connected by the outer housing. However, the outer housing is not the only connection. The wires connect the four subassemblies together too.

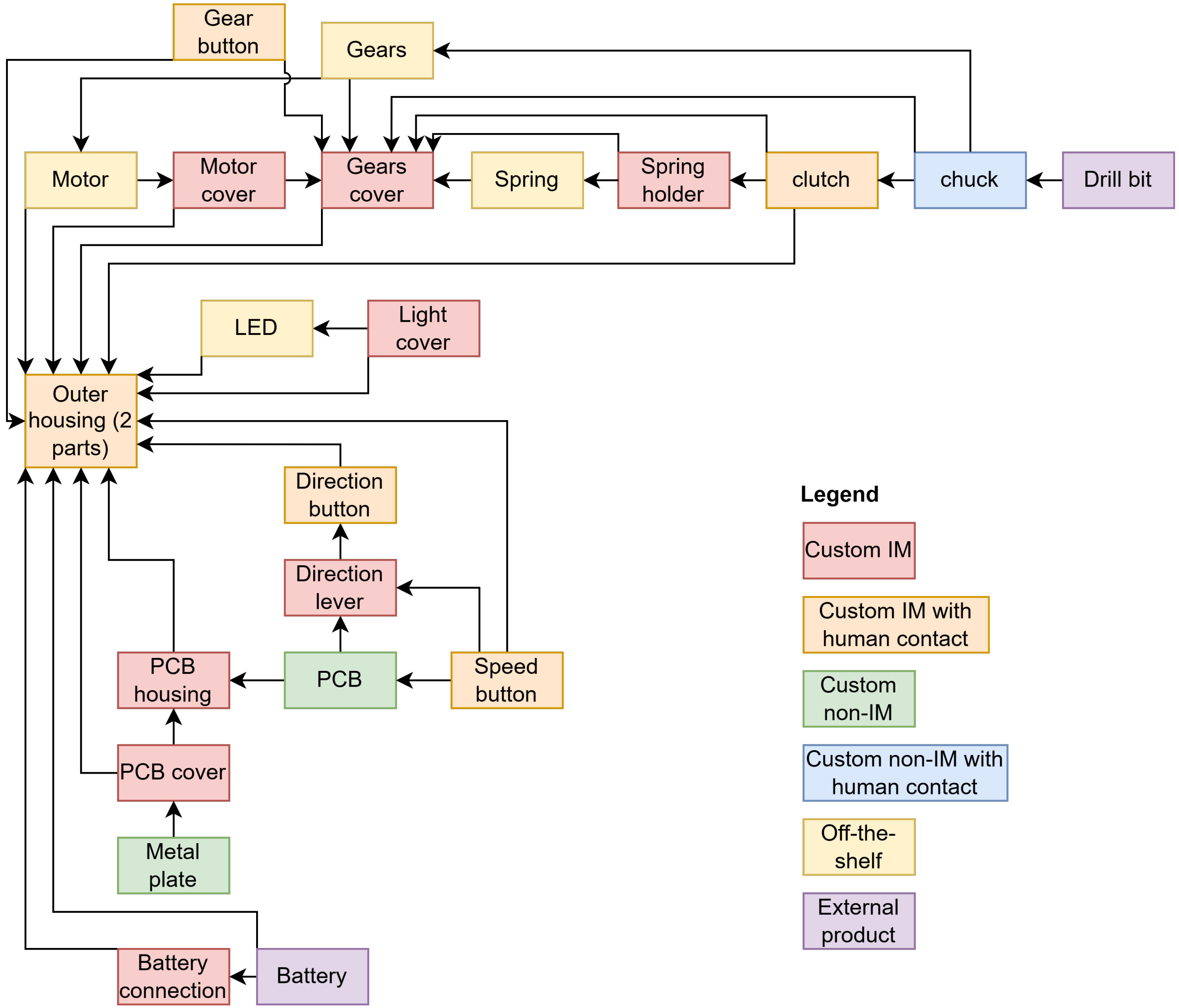


Figure 100: Product architecture map of the Ferm cordless drill, version 2.

Version 3 (Figure 101) differentiates between different connection types of parts. However, it was uncertain whether the electrical connection should be included in the map.

Figure 102 and Figure 103 show the same graph as version 3, but with an exploration made to see if it would be clearer to swap out the part names for their functions. However, some parts have multiple functions, so then it becomes unclear how to name the part. The following part functions were found in the drill:

- Power
- Conduction
- Heat transfer
- Control
- Human control
- Mechanics
- Lighting
- Mounting
- Part containment

Overlaying the product architecture map over a photo of the product also does not improve the map. Some parts are not visible and many text boxes are too close together to understand what is going on. It would be even more confusing with a more complex product.

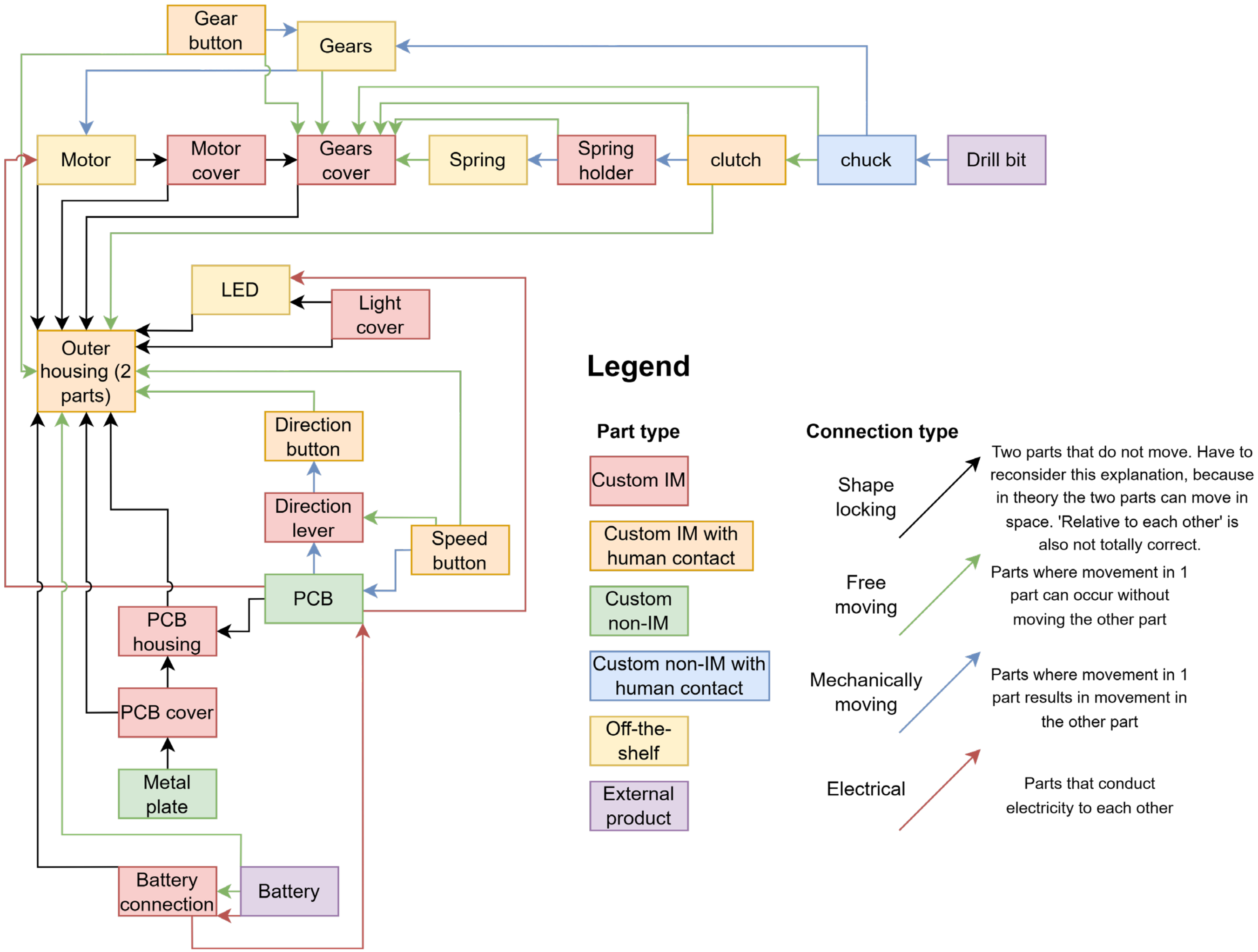


Figure 101: Product architecture map of the Ferm cordless drill, version 3.

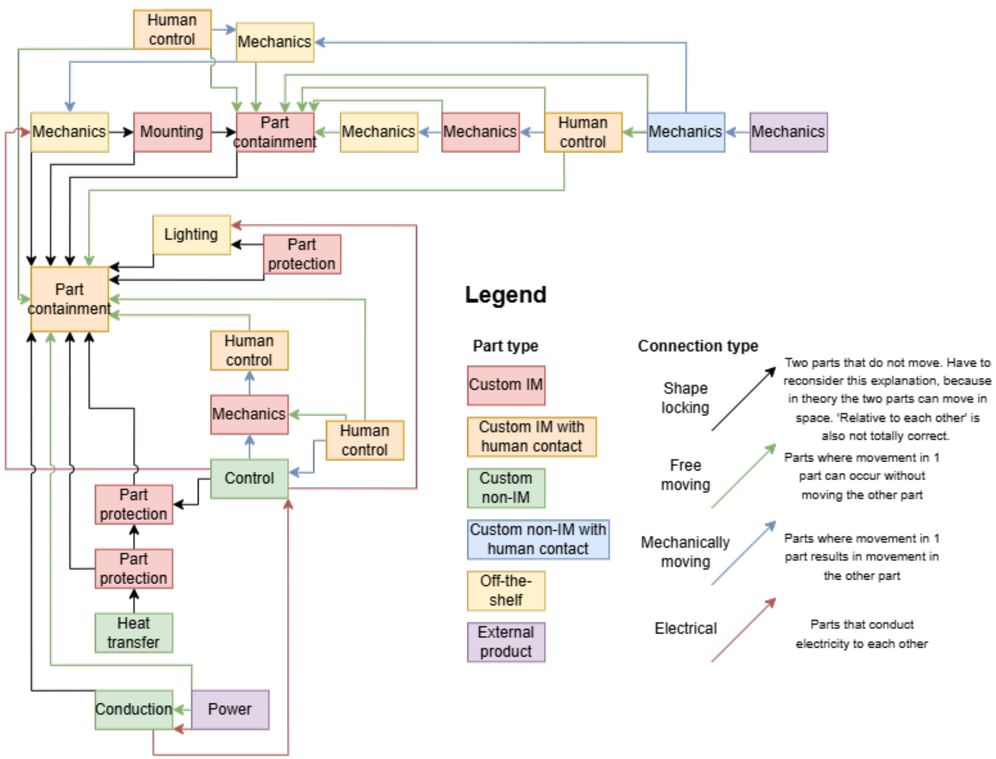


Figure 102: Product architecture map of the Ferm cordless drill, version 4.

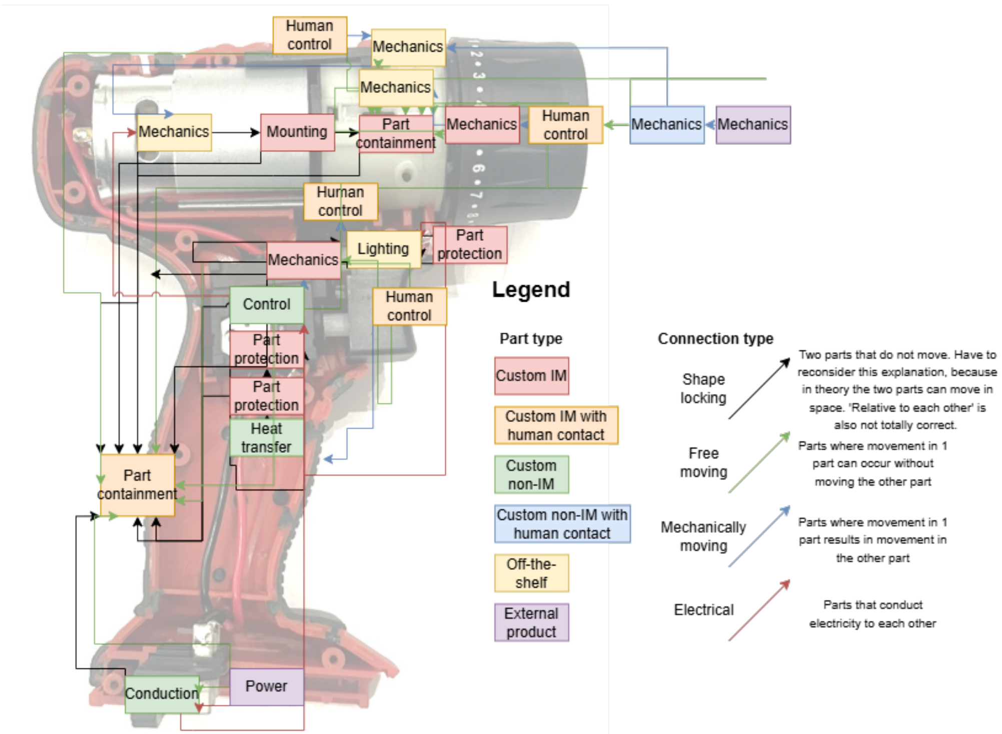


Figure 103: Product architecture map of the Ferm cordless drill, version 5.

The next version (Figure 104) was the latest version before final version from Chapter 4.1 (Figure 22). The following changes were made:

- Electrical connections were indicated with a symbol rather than as a connection type.
- Parts with human contact were indicated with a symbol instead of as a separate part type.
- Small adjustments were made to part connections.
- Arrows indicate part priority on geometry and placement.

A discussion point regarding the part priority: the PCB assembly is placed relatively arbitrarily in the outer housing. The PCB housing and PCB cover both influence the shape of the outer housing, but one could not be moved without also moving the other. This was now indicated with arrows from both parts. Maybe this could be solved in a different way, for example by indicating separate subassemblies in the product architecture map.

As can be seen in the map, it is mostly the off-the-shelf parts that were assumed to have had priority in geometry over the custom IM parts. This also makes sense, because a custom IM part can be designed to fit around an off-the-shelf part, whereas the choice in off-the-shelf parts is limited and designers have to work with what they can get.

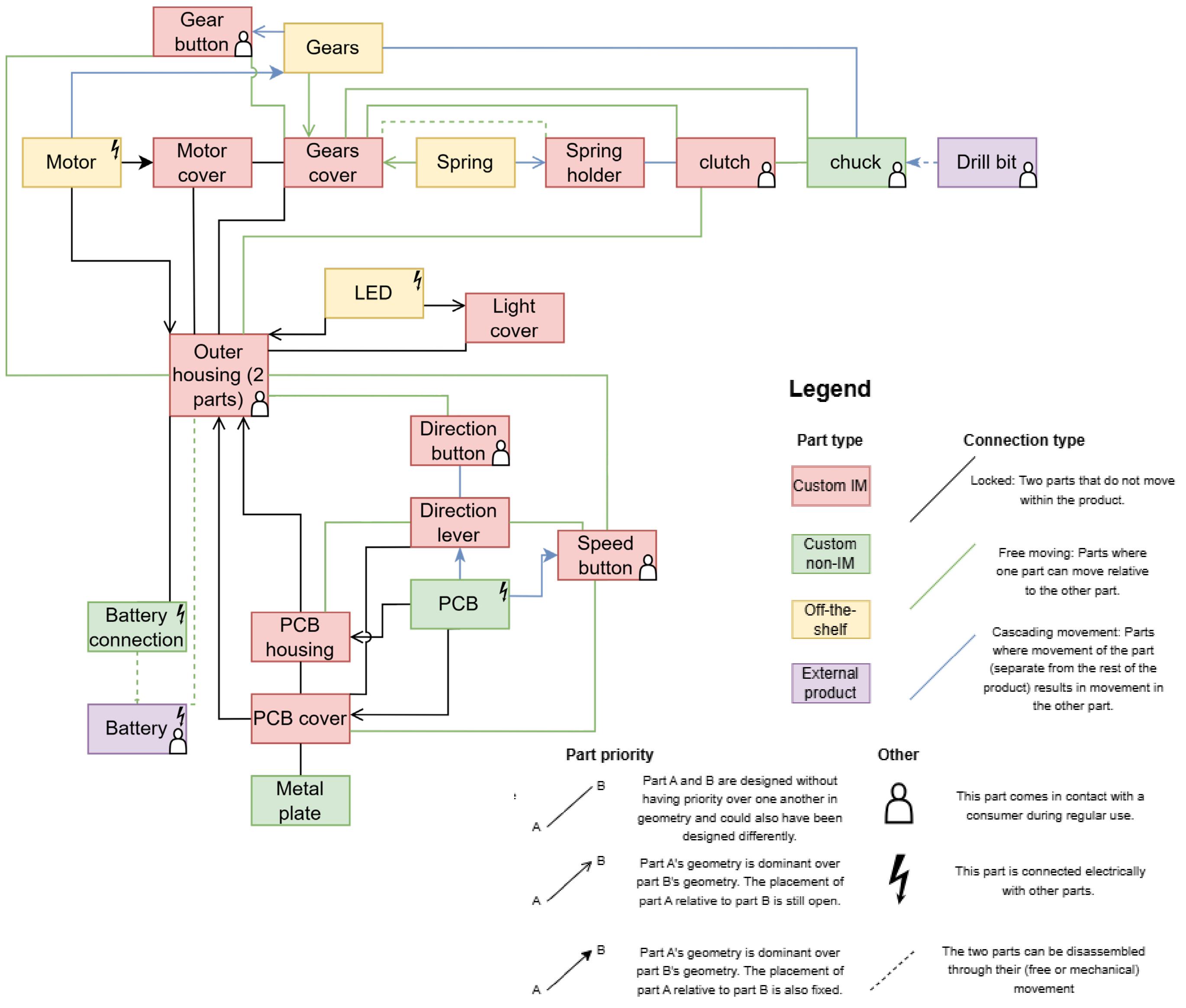


Figure 104: Product architecture map of the Ferm cordless drill, version 6.

Disassembly map vs. product architecture map

In this section, the applicability of a disassembly map for showing geometric connections between parts is evaluated. The Disassembly Map method (De Fazio et al., 2021) points out how parts are related to each other, by the disassembly steps that it takes to reach a part. For example, in Figure 105, parts 2, 3, 4, 5, 6, 8, 9, 10, 13, 14 and 15 need to be removed to get to part 30. This method is mostly meant for analysing once a product is already designed. The positive aspect about using a disassembly map is the fact that components can always be traced back to a certain connection or part. Furthermore, this is an acknowledged method which would improve transferability across the field.

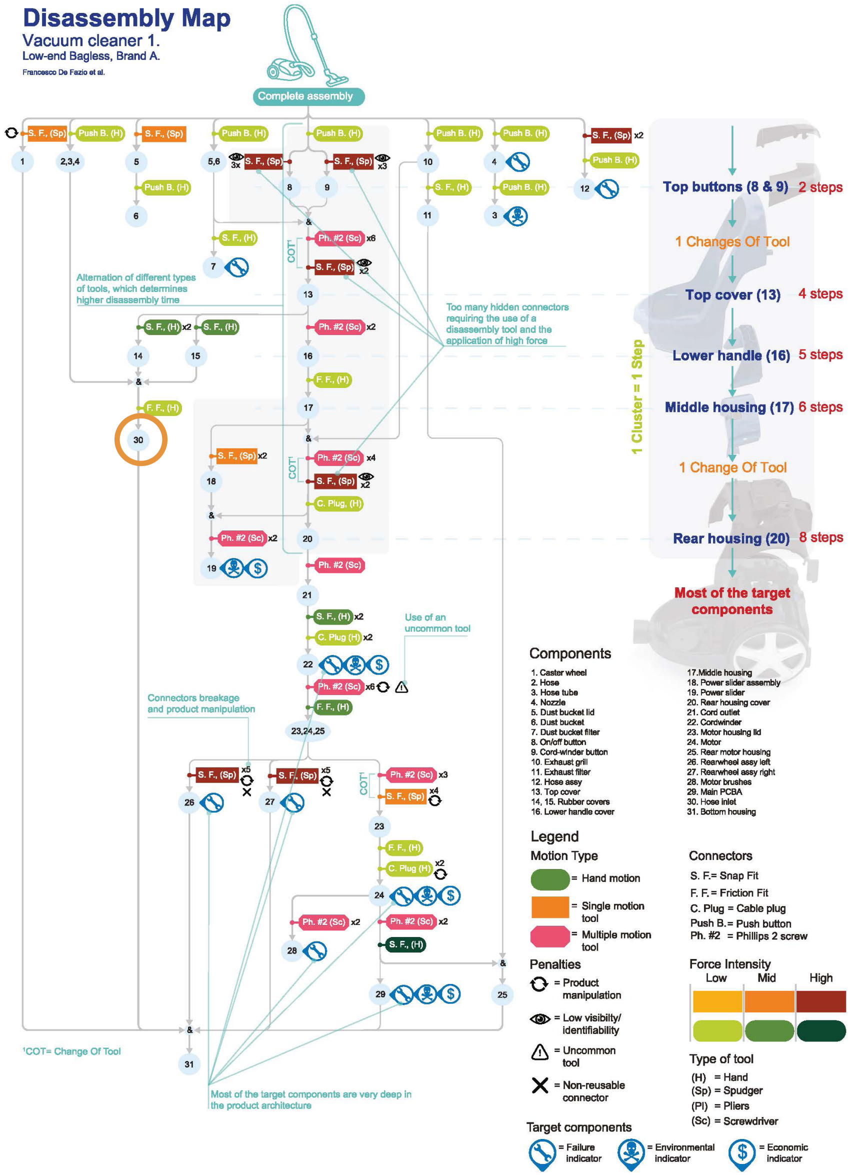
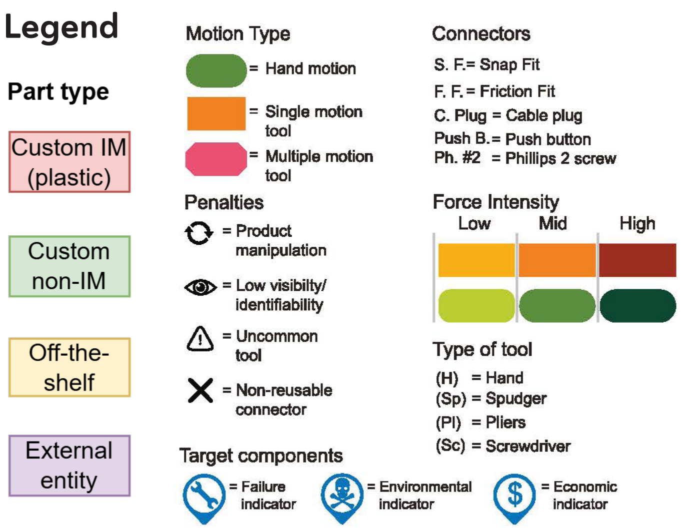


Figure 105: Disassembly map of a vacuum cleaner (De Fazio et al., 2021).

Figure 106 shows the disassembly map of the Ferm cordless drill. Although it shows how one part influences the next in the required steps to isolate a part during disassembly, there is no clear overview of which components directly influence each other's geometry. For example, the chuck is a component that can only be removed once the left and right housing are removed (Figure 107), amongst other steps. However, the product architecture map (Figure 108) shows that there is no direct relation between the left and right housing and chuck. This creates 'false positives', indicating that parts influence each other's geometry, whereas this is not directly the case. This thus unnecessarily complicates the (re) design process.



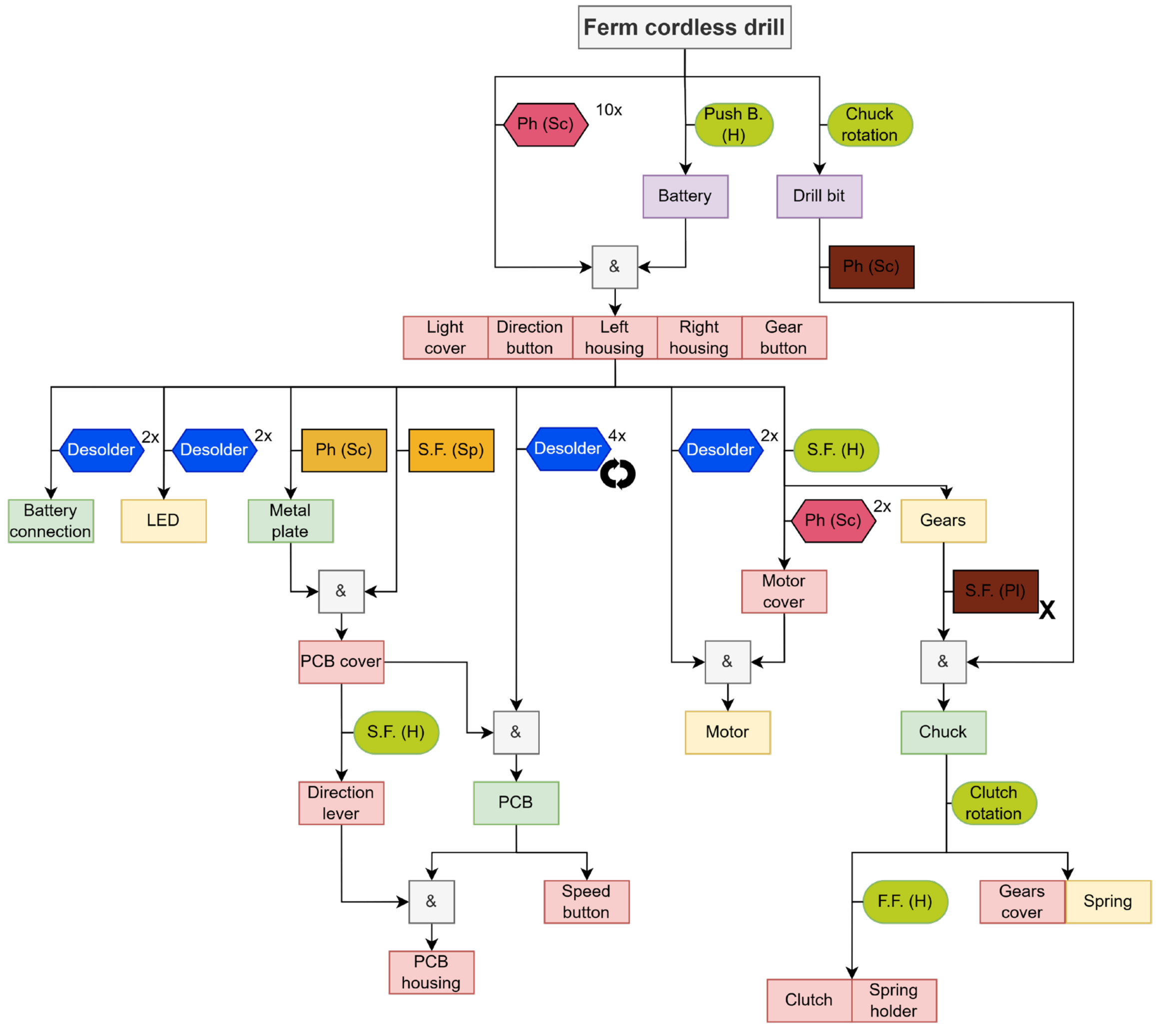


Figure 106: The disassembly map of the Ferm cordless drill, composed with the method by De Fazio et al. (2021). Note: parts were named and colour coded with the geometry-based part coupling approach, whereas the method originally uses numbers in a circle to indicate parts. If multiple parts are revealed by a disassembly step, these are grouped together in the Disassembly Map method. In this disassembly map, each part was named separately. When multiple parts are revealed by a disassembly step, this version of the disassembly map still puts the parts in different boxes (placed adjacently). This change was made so a distinguishment could be made in the geometry-based part coupling approach to indicate more precisely which parts are coupled. Also, the action block 'desolder' is not originally included in the Disassembly Map method but is included here to provide more detailed information on the required disassembly steps.

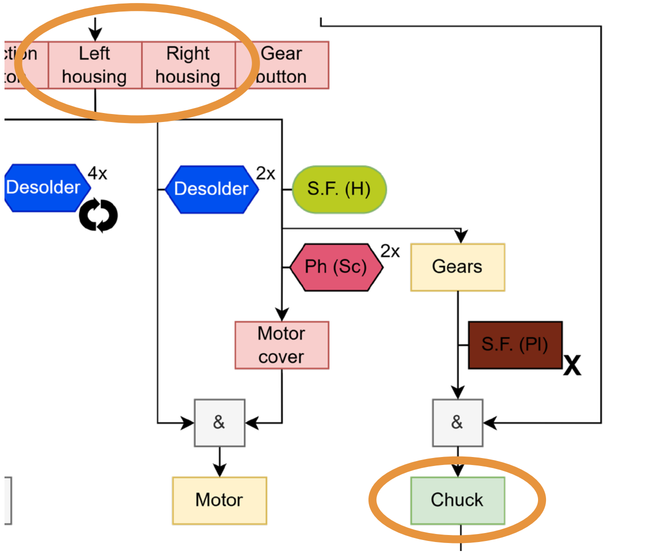


Figure 107: The chuck connection to the left and right housing in the disassembly map.

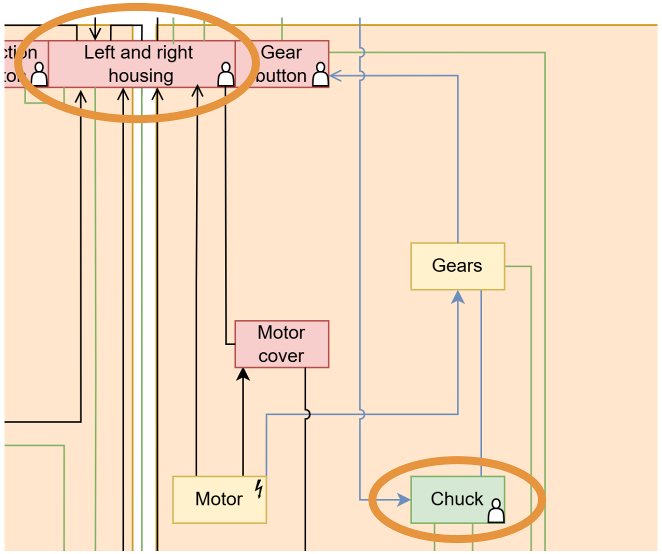


Figure 108: The non-existing connection of the chuck to left and right housing in the product architecture map.

Another example: the PCB cover and PCB housing are still connected together with a snap fit after removing the metal plate. When redesigning the PCB cover for AM, it must thus still fit with the PCB. The product architecture map (Figure 109) shows a direct, shape locking connection between the two parts. The snap fit connection of the two parts in the disassembly map (indicated in green in Figure 110) does not clearly indicate that that is how those two parts are connected.

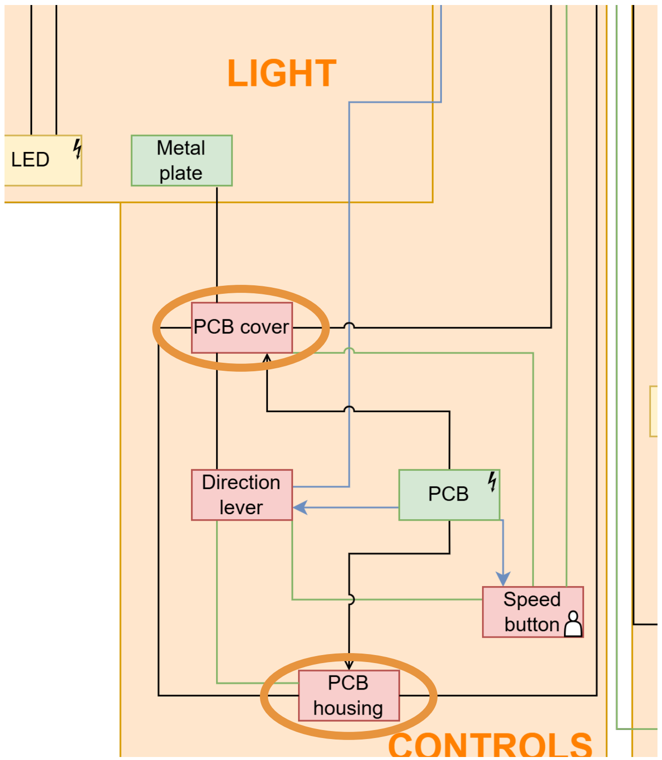


Figure 109: The PCB housing connection to the PCB cover in the product architecture map.

To conclude, the preferred method to indicate the geometric part coupling to use is the one as shown in Figure 22. However, because the Disassembly Map method is an established method, the product architecture map used the same positioning of components as in the disassembly map. Therefore, it can be used as an 'overlay' of additional information. Other tools that have used the disassembly map as a basis for additional information are the combination with a hotspot map (Flipsen et al., 2020) by Bahlmann (2023) and the recyclability map by Versloot (2024).

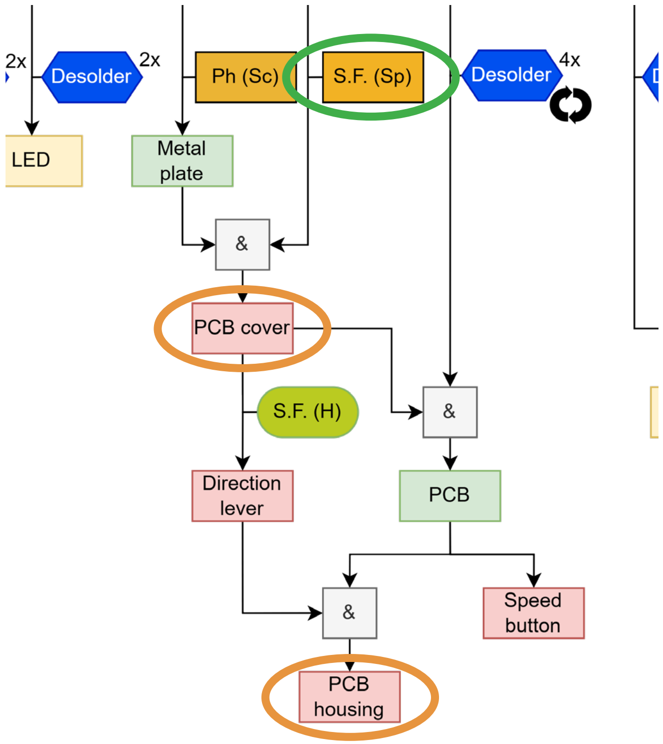


Figure 110: The PCB housing connection to the PCB cover in the disassembly map.

Appendix F | Exploration of parametric part definition

An exploration was made to fully define a part's function geometrically. Because the design approach was considered to be complex and not intuitive for the natural workflow, this design approach was not further explored than what is described below.

The steam setter holder of the Tefal iron FV1711 was defined parametrically. Eleven Design Degrees of Freedom were initially needed to define a mechanism, fixed in the top shell, that turns rotational movement (of the button) into a vertical translation (of the descaler rod) (Figure 111). This must fit within the defined design space Figure 112. However, after defining the eleven Design Degrees of Freedom, a design direction had to be chosen to further develop the steam setting mechanism. In the Tefal iron FV1711, the choice was made to design a slotted crank and link mechanism. After this decision, more Design Degrees of Freedom could be added, such as the slot axis. Another step would be more elaborately define the snap fits that fix the mechanism to the top shell. Torossian and Bourrell (2015) describe ways to parametrically define three types of snap fits.

With a parametrically defined part, the next step is to develop and model the features. Jong et al. (2011) explore an automation of the step from a parametrically defined part to a developed part with the features modelled. Maidin et al. (2011) lists various common features that can be used in AM. Tang et al. (2016) explore how aspects of a part described with functions, such as the parametrically defined part in Figure 111, can be merged so one part performs multiple functions. However, all these options were not explored.

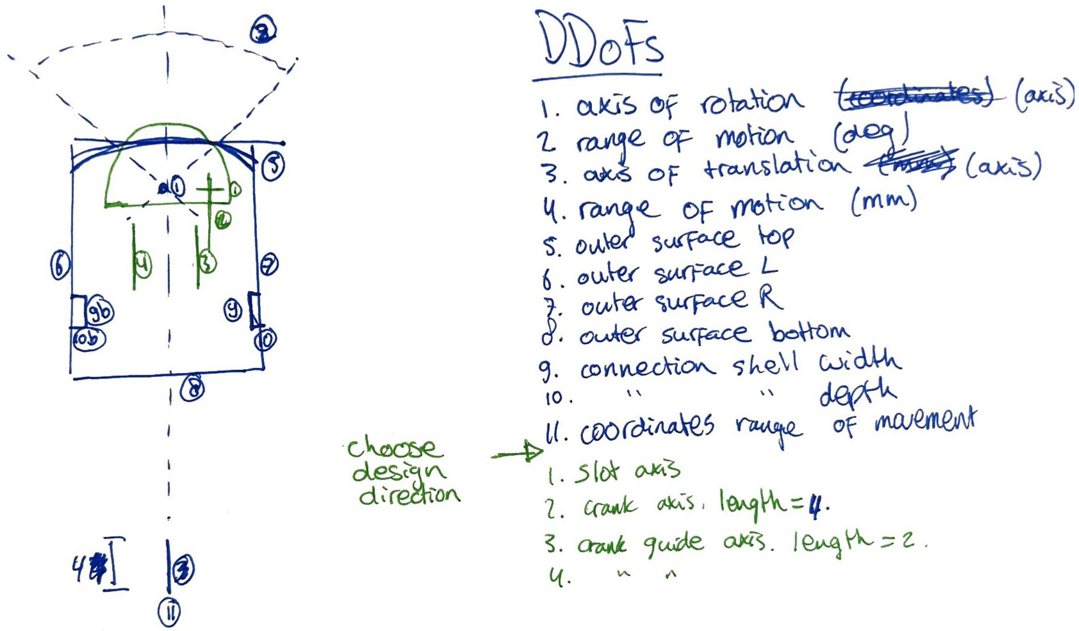


Figure 111: The steam setting mechanism defined parametrically.

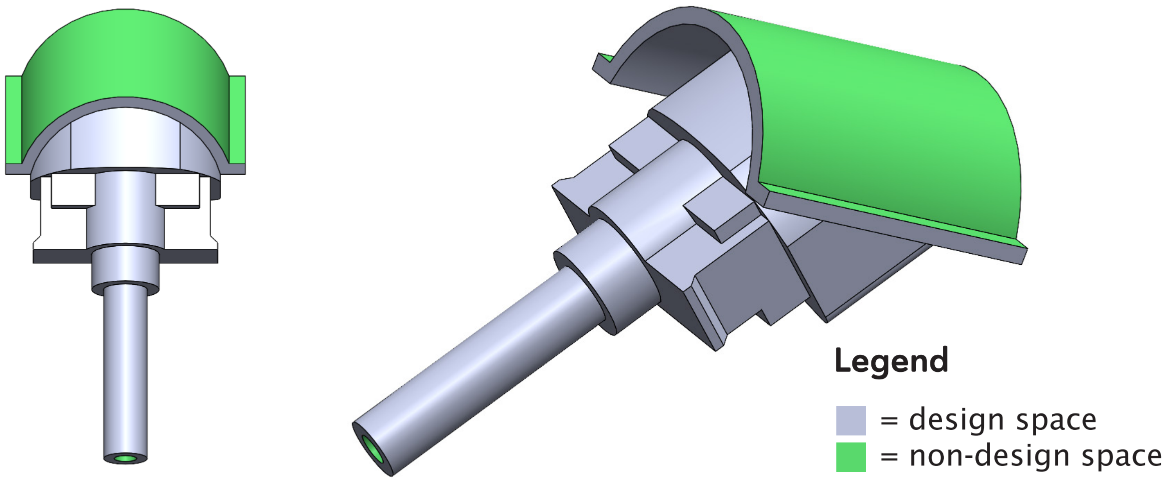


Figure 112: The design space and non-design space (form factor) for the steam setting assembly.

Appendix G | Alternative design strategies

Multiple design strategies were considered for exploration, which can be sorted based on two parameters:

- The IM and SLA part identicality
- The manufacturing priority of IM or SLA

The design strategies are listed in Table 19 and visualised in Figure 113. The explored form factor optimisation guide does not prioritise IM or SLA and does not necessarily yield identical parts.

Table 19: Design strategies sorted on part identicality and manufacturing priority.

<table>
<tr><th></th><th colspan="3">IM and SLA part identicality</th></tr>
<tr><td rowspan="4">Manufacturing priority</td><td></td><td>Identical</td><td>Not identical</td></tr>
<tr><td>IM</td><td rowspan="3">Any strategy here is manufacturing driven (Klahn et al., 2015). Diegel et al. (2019) refer to this as ‘direct part replacement’. No matter which manufacturing technology has priority, the part’s geometry can be produced identically with either technology. This thus does not use the full range of capabilities of either technology.

An alternative design solution is ‘rapid tooling’ (Lozano et al., 2022), where a mould is produced with SLA. This mould can be used in low batch sizes to injection mould plastic parts. However, this method was not considered.

(Figure 113, strategy 1,2,5)</td><td>This is referred to as ‘adapt for IM’ by Diegel et al. (2019), which uses the IM part as a basis to produce the SLA part. This is manufacturing driven and may not yield an optimal SLA part because it is built from the manufacturing limitations of IM.

(Figure 113, strategy 3)</td></tr>
<tr><td>No priority</td><td>The newly developed form factor optimisation guide is placed here, where two interchangeable but not necessarily identical parts produced with IM and SLA are the result of optimising the part’s form factor. As shown in Figure 113, this can still end up with the same results as in other methods. The blue model shown in Figure 113.6 represents the form factor of the part.

(Figure 113, strategy 6)</td></tr>
<tr><td>SLA</td><td>Using a function driven design strategy, a part can be optimised to use the capabilities of SLA (Klahn et al., 2015). However, because SLA has a larger range of capabilities than IM, it may not be possible to transfer this design to IM.

(Figure 113, strategy 4)</td></tr>
</table>

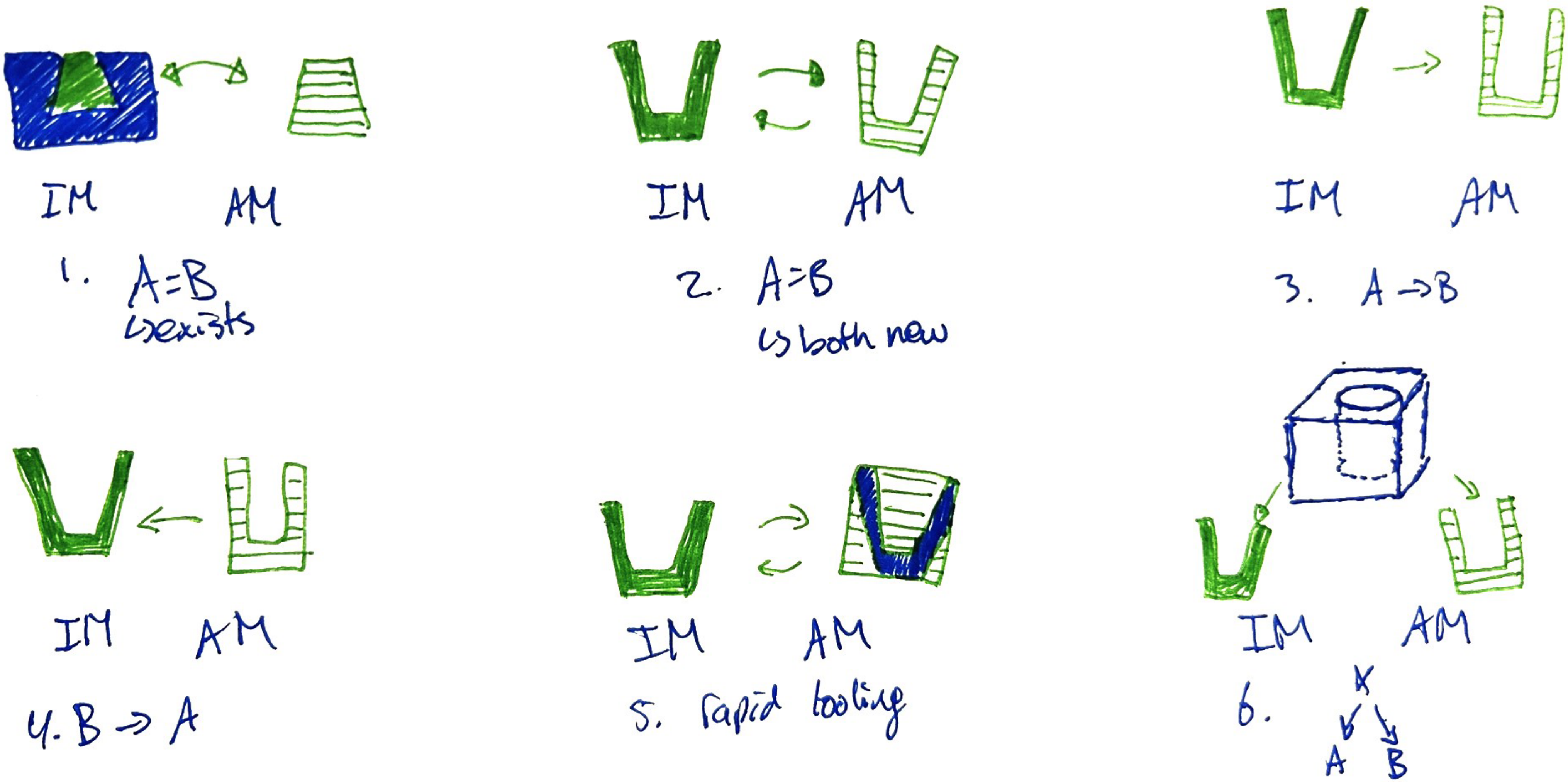


Figure 113: Design strategies visualised.

Appendix H | Case study pen

Additional information on the list of requirements

The pen tip is made from metal and the pen housing is made from plastic. Both parts are injection moulded. The mould design layout of the pen tip and pen housing are graphically indicated in Figure 114.

The mould of the pen tip consists of four pieces: two that move horizontally around the screw thread and two that move vertically. The pen tip has a flat spot on the threads, which is there to avoid negative draft angles on the horizontally moving mould pieces.

The pen housing's mould consists of two pieces that move along the rotational axis of the housing. The screw thread in the housing is most likely made with a part of the mould that is able to turn out after producing the screw thread. A mould piece is injected all the way from the top of the pen (pen tip side) to the bottom (pen cap side) on the inside.

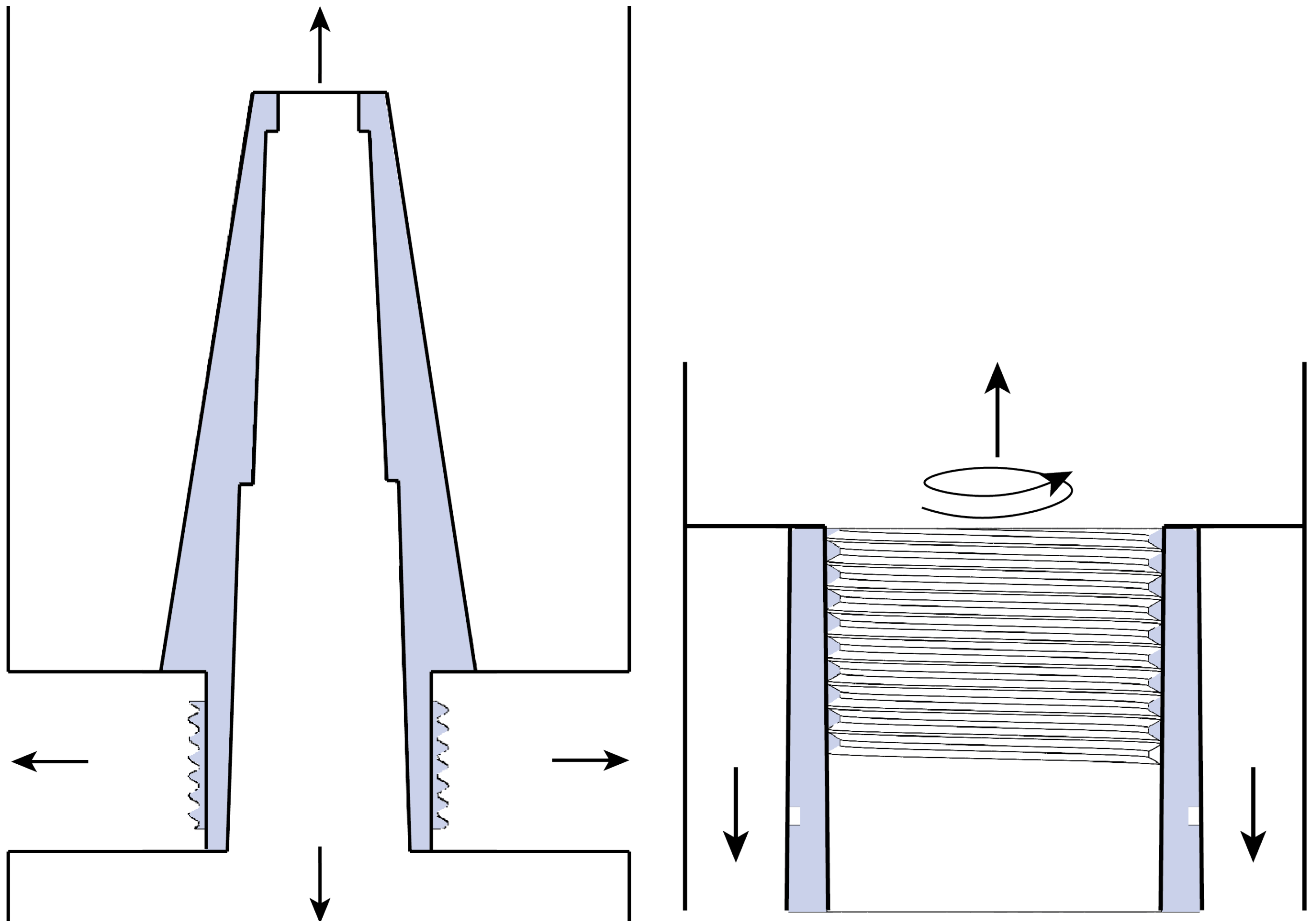
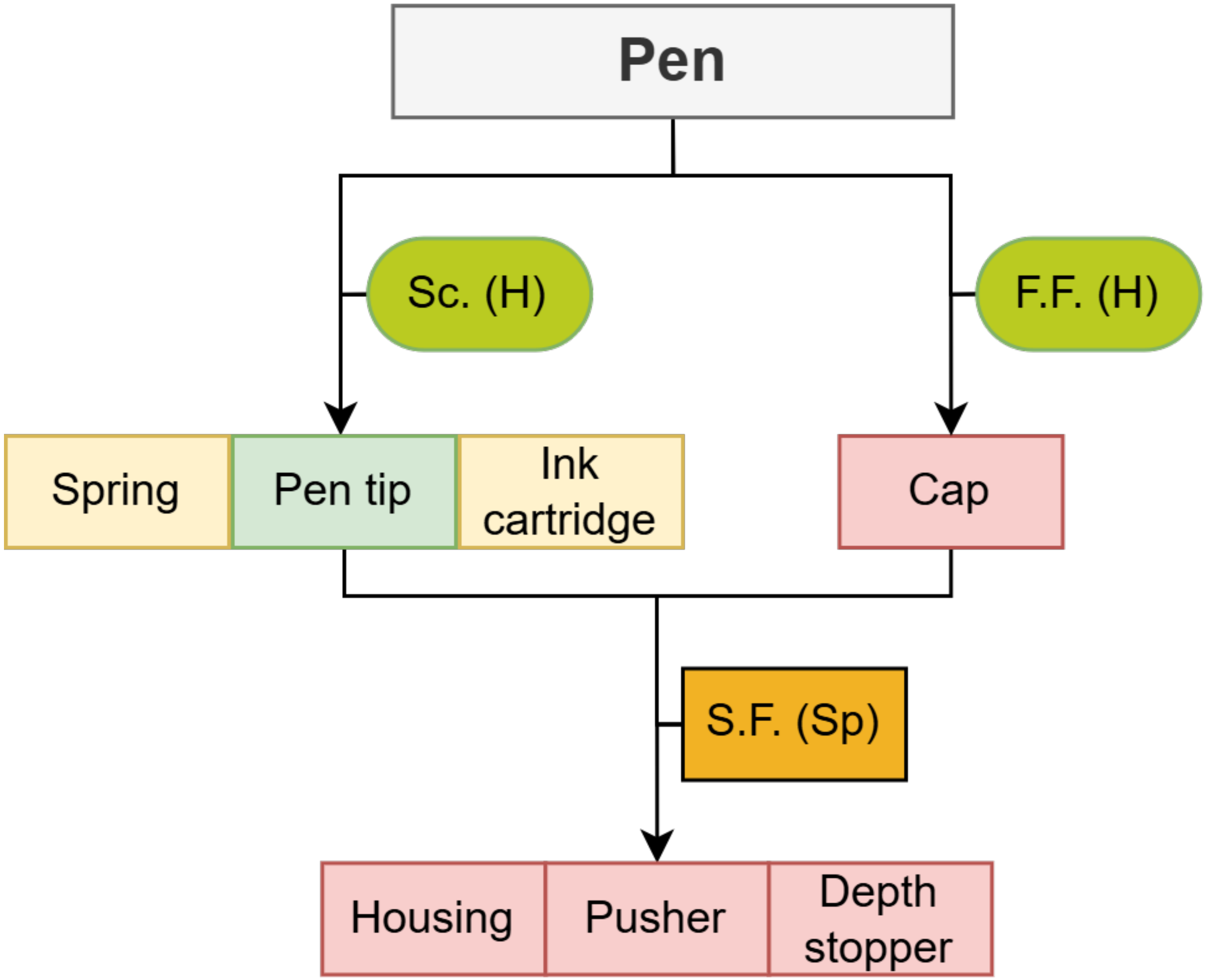


Figure 114: The current mould design layouts of the pen tip (left) and pen housing (right). Only the top part of the pen housing is shown.

Disassembly map

The disassembly map of the pen was composed using the method by De Fazio et al. (2021). The disassembly map is shown in Figure 115.



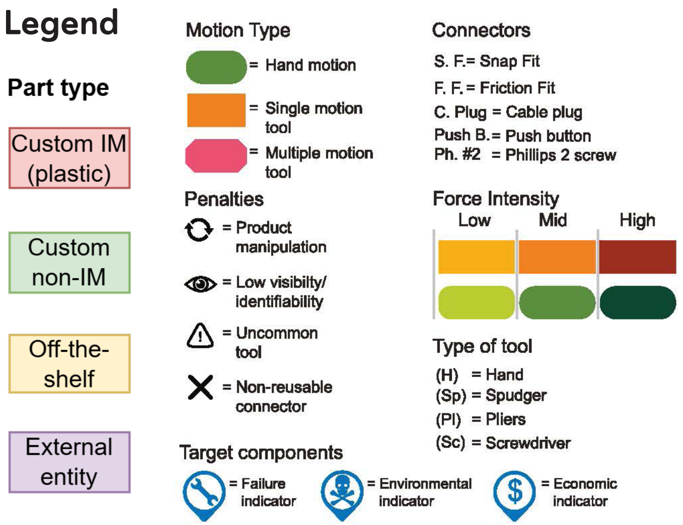


Figure 115: The disassembly map of the pen, composed using the method by De Fazio et al. (2021).

Full product architecture map

The product architecture map of the pen (Figure 116), composed with the geometry-based part coupling approach, shows regarding the components that influence the pen tip and housing's combined form factor (Figure 117) that:

- The pen tip is a custom non-IM part, indicated by the green rectangle. The housing is a custom IM part, indicated by the red rectangle.
- The pen tip is coupled with the spring, the ink cartridge and the housing, indicated with the lines that connect the parts.
- The coupled interface type between the spring and pen tip is 'relative displacement', indicated with the green line colour. This is because the spring can move without moving the pen tip. The spring also has geometric and positional priority over the pen tip, as indicated with the solid arrowhead.
- The coupled interface type between the ink cartridge and pen tip is also 'relative displacement', indicated with the green line colour. This is because the ink cartridge can be displaced without displacing the pen tip. The ink cartridge also has geometric and positional priority over the pen tip, as indicated with the solid arrowhead.
- The coupled interface type between the housing and pen tip is 'static', indicated with the black line colour. This is because there is no movement of the pen tip and housing relative to the product. There is no form of geometry priority, as indicated by the lack of an arrowhead.
- The housing and pen tip come in contact with the user during regular use, as indicated by the human figure icon.
- The parts that are connected to the housing are the pen tip, pusher, depth stopper and cap. However, because the pusher, depth stopper and cap fall outside of the scope of this design problem, these relationships are not analysed further.

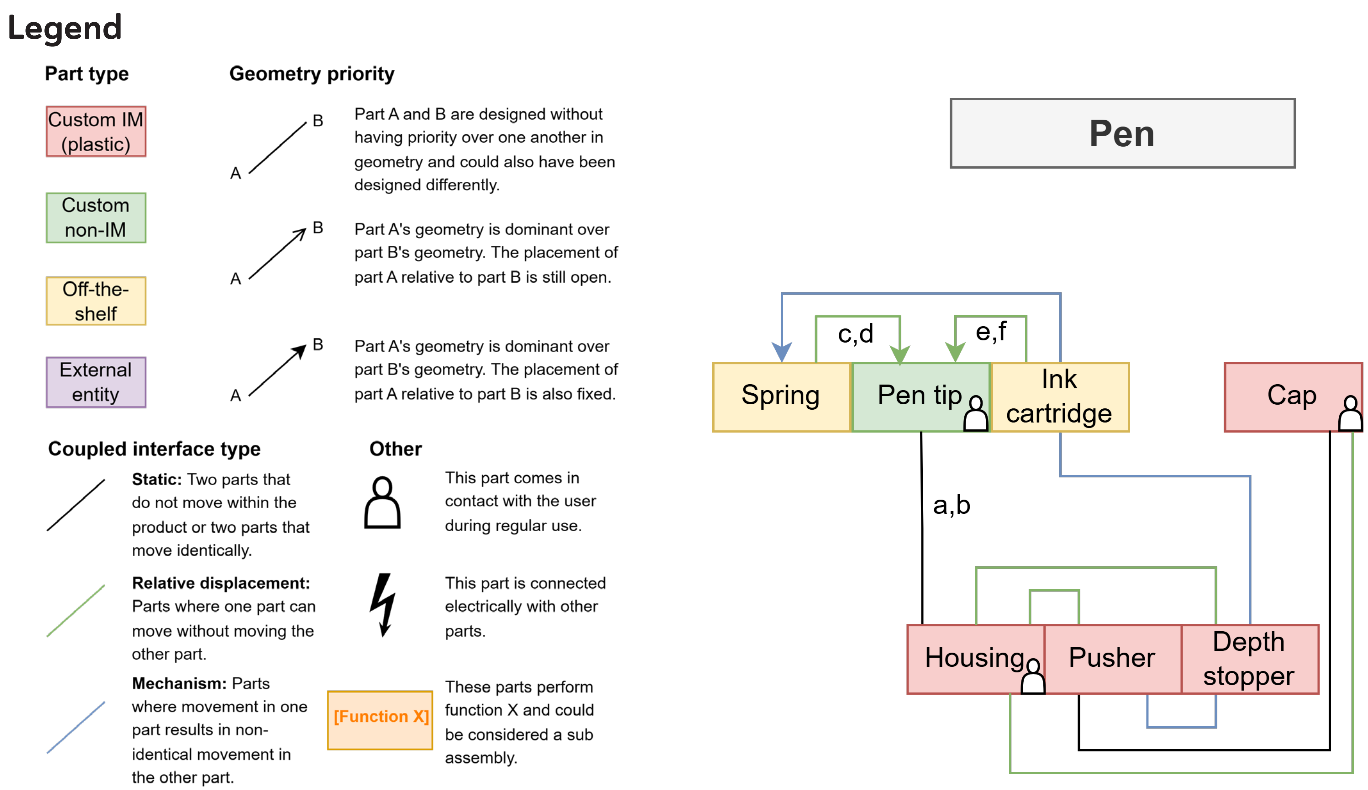


Figure 116: The product architecture map of the pen, composed with the geometry-based part coupling approach, annotated with the functional surfaces.

Form factor

The analysis of the geometry of the parts showed that the non-design space is defined by the following functional surfaces:

a. A transition fit between the pen tip and housing.
b. Matching diameters of the pen tip and housing.
c. A clearance fit with between the pen tip and spring diameter.
d. A surface for the spring to sit against.
e. A clearance fit with between the pen tip and ink cartridge diameter.
f. A clearance fit with between the pen tip and ink cartridge tip diameter.

The design space and non-design space were mapped over the model of the pen tip and housing in Figure 117. The annotated product architecture map (Figure 116) shows which coupled parts result in which functional surfaces.

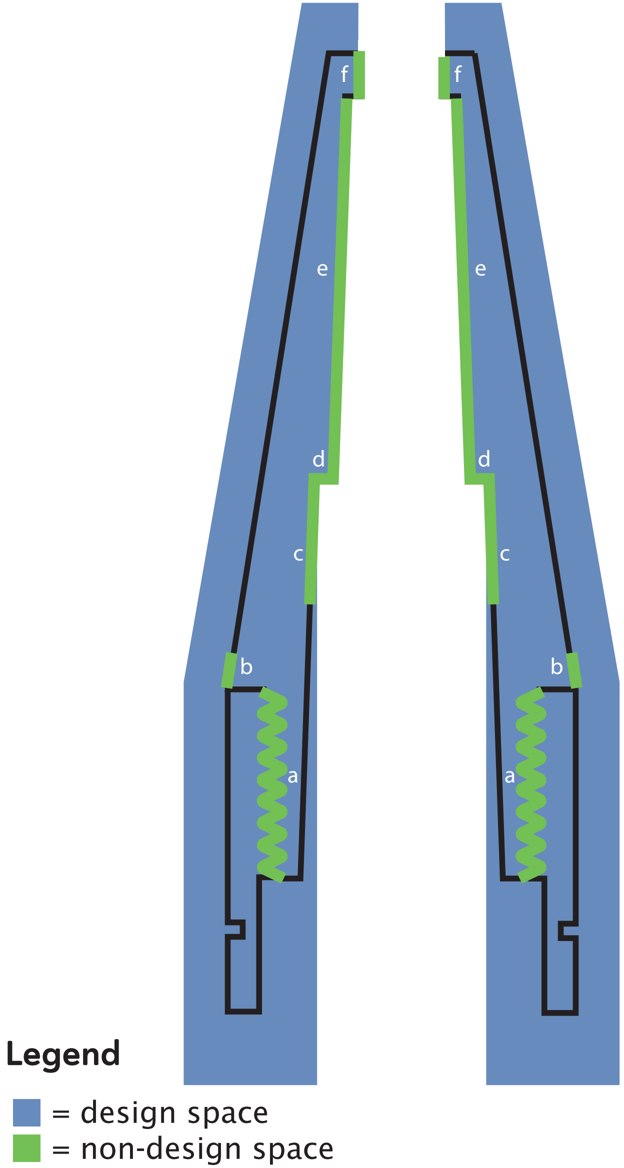


Figure 117: The form factor of the pen tip and housing.

Ideation

Figure 118 shows some of the ideas generated for the pen tip connection to the housing.

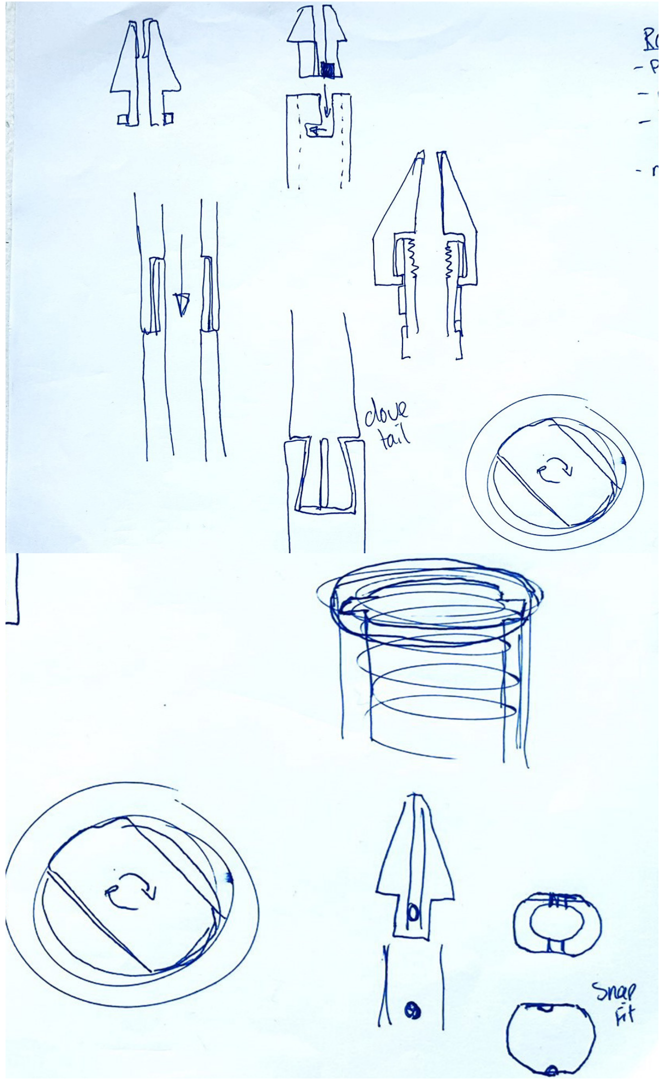


Figure 118: Ideas for the connection of the pen tip to the housing.

FDM prototypes

Figure 119 shows the FDM prototypes that were made to validate the designs before waiting for the SLA parts to be manufactured.

Figure 119: The FDM prototypes of the pen redesigns. They were made on a 4:1 scale.

Post-processed threads

Figure 120 shows the result of trying to tap the threads on the SLA pen tip and housing, which did not succeed. Whilst tapping the screw threads on the manufactured SLA parts, the pen tip's screw thread stripped and the housing tore. Because the housing does show some successful threads, it is assumed that the post-processing failed due to lack of a proper set-up. With a professional OEM set-up it is assumed that the post-processing does not result in issues with creating the screw thread and the pen tip can be connected to the spare housing with the tapped screw threads.

A thread size of M7x1.0 was used in the prototypes instead of the original thread size, due to lack of access to the tools to produce the original threads. To be able to match the threads of the housing in the pen tip, the pen tip was also manufactured. In an OEM setting, the housing would be tapped with the same thread size as the original pen tip.

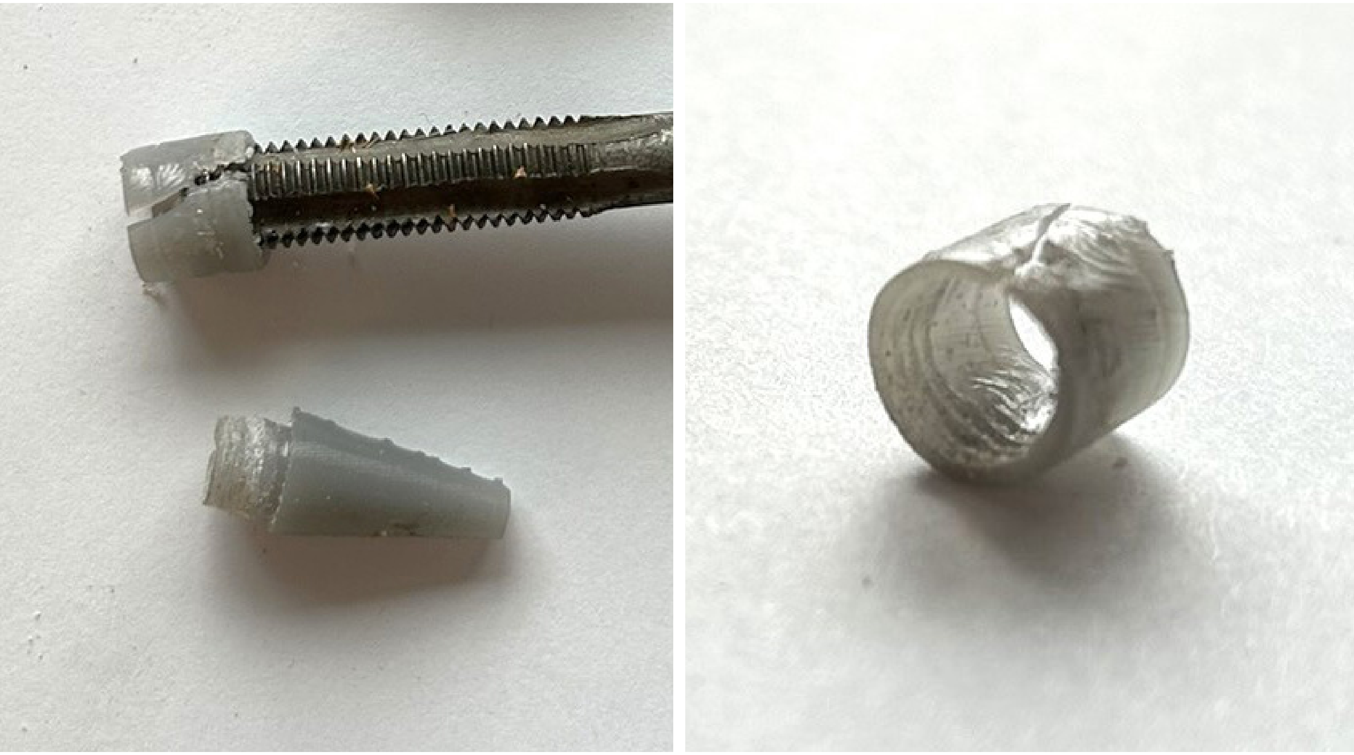


Figure 120: Tapping the screw threads during post-processing was not successful.

Bayonet closure

The fourth concept was the most complex to design and manufacture. An FDM prototype (Figure 119) was produced to evaluate the snap of the outdents on the J-track and housing, so it stays in place firmly. The transition fit between the outdents was given more clearance for the SLA prototype. Support removal from the inside of the housing, without damaging the outdent, was also challenging. This is something that should be improved in future iterations of this design concept.

Appendix I | Case study snap fits

Additional information on list of requirements

Figure 121 shows the mould design layouts of the steam setter holder and top shell, annotated over pictures of the parts. The steam setter holder has mould parts moving in six directions, whereas the top shell moulds move in three directions.

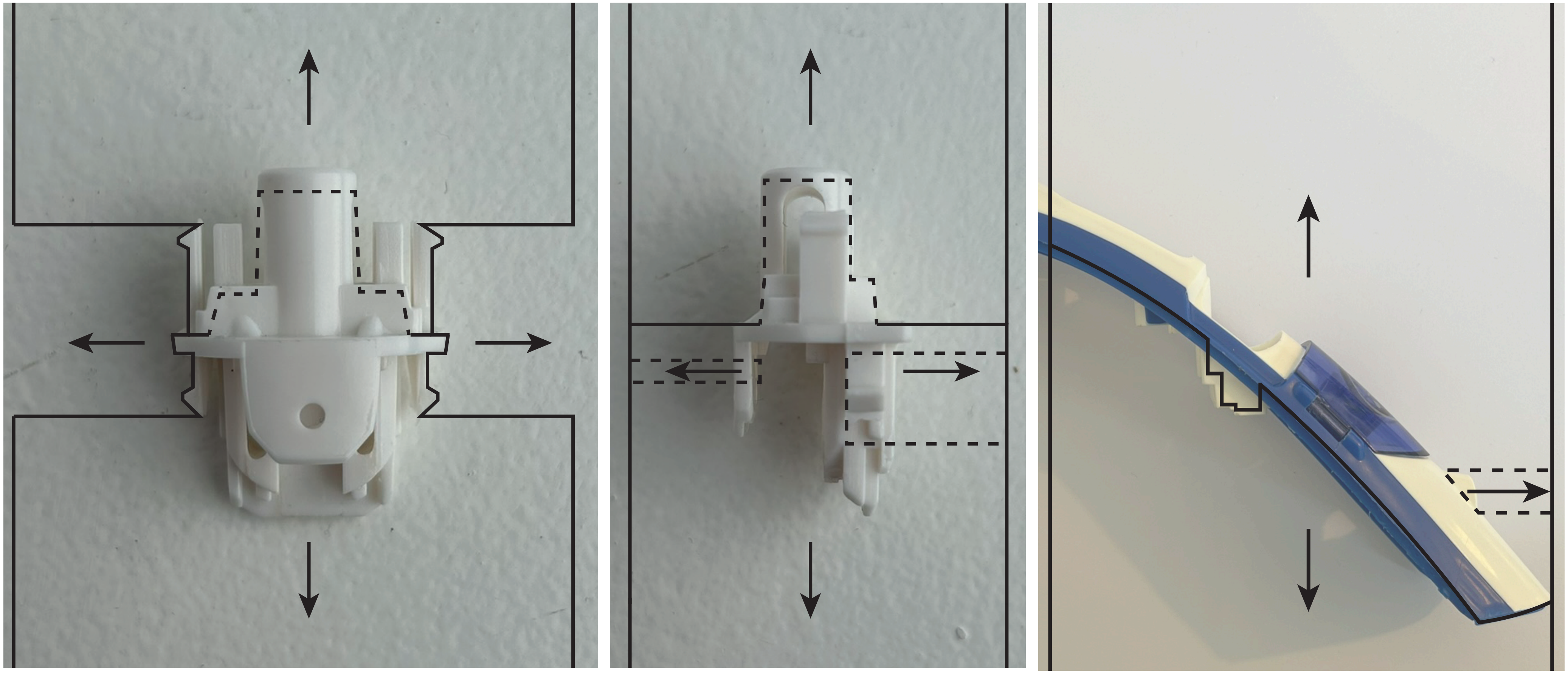
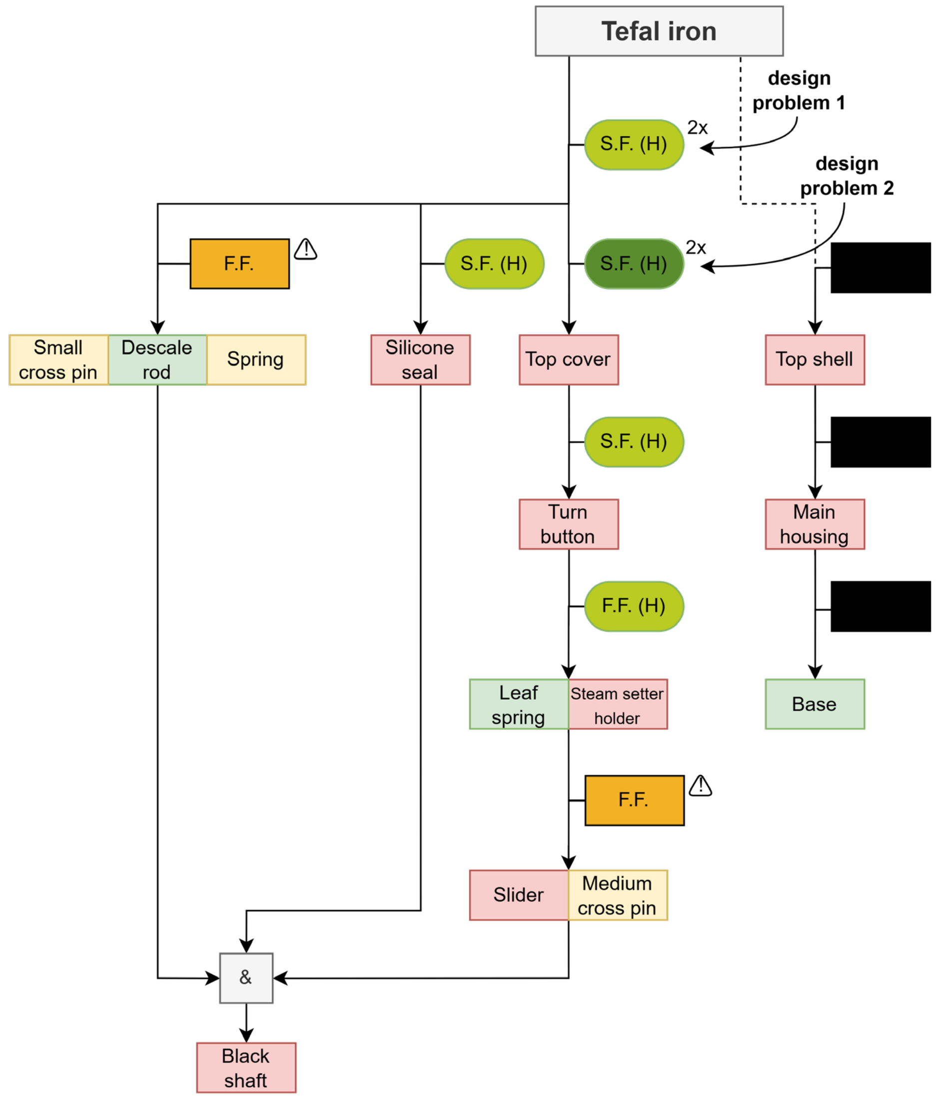


Figure 121: Annotated pictures of the mould design layouts of the steam setter holder (left and middle) and the top shell (right).

Disassembly map

The disassembly map of the steam setting assembly was composed using the method by De Fazio et al. (2021). The disassembly map is shown in Figure 122.



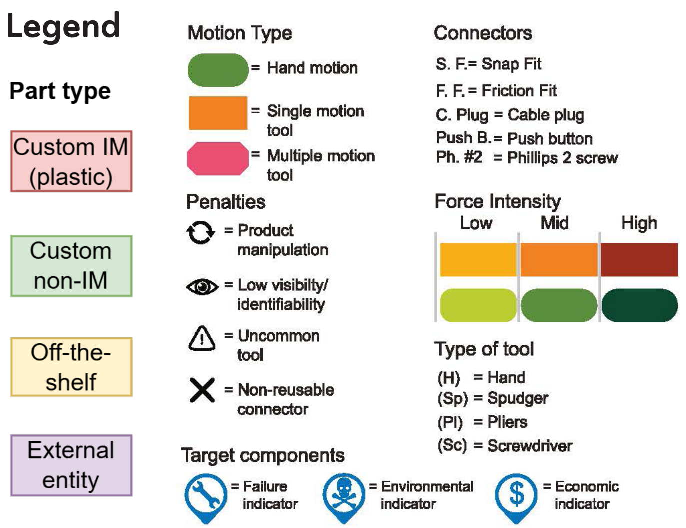


Figure 122: The disassembly map of the steam setting assembly and the components that influence the geometry. The snap fits of the two mentioned design problems are annotated. Note: the disassembly steps for the top shell, main housing and base are represented with black boxes. These disassembly steps are not further explored and thus simplified.

Product architecture map

The full product architecture map of the steam setting assembly with all functional surfaces from the form factor annotated is shown in Figure 123.

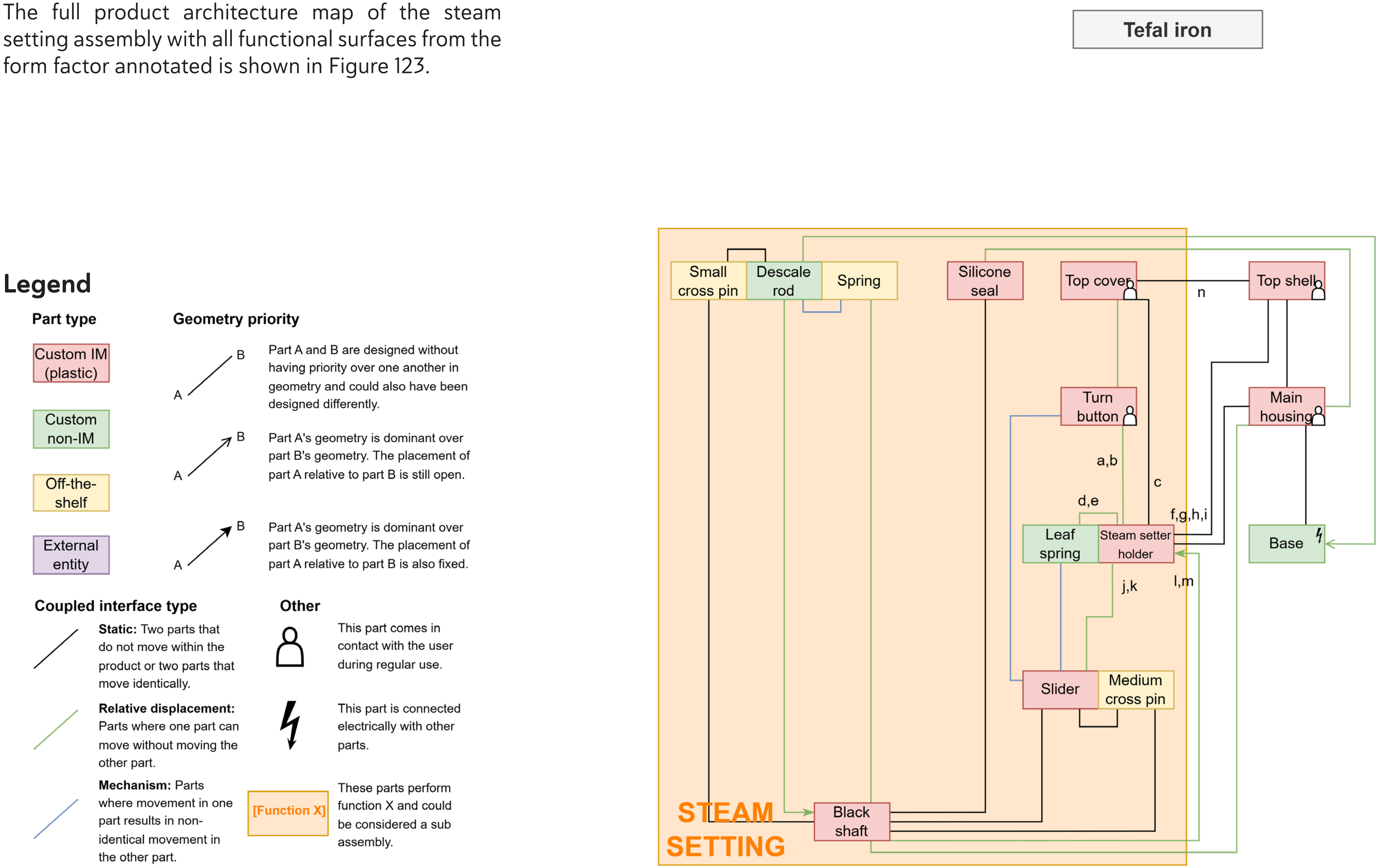
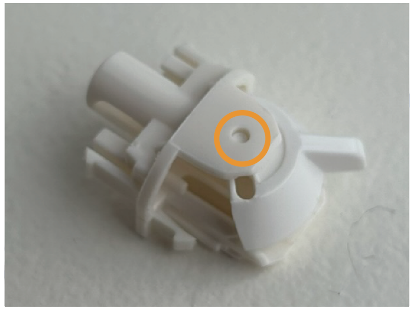


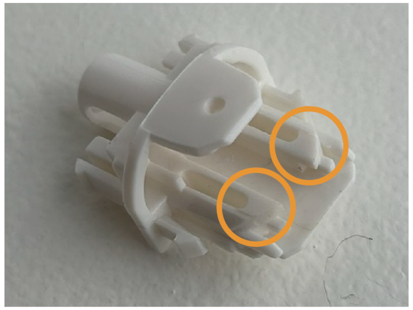
Figure 123: The product architecture map of the steam setting assembly and the components that influence the geometry, composed with the geometry-based part coupling approach.

Form factor

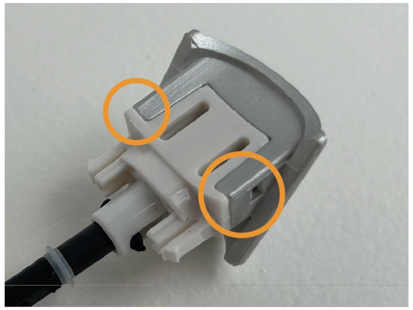
Figure 124 shows an elaboration of all functional surfaces of the steam setter holder.



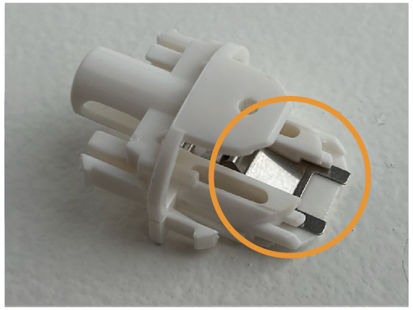
a: Clearance fit with the turn button axle



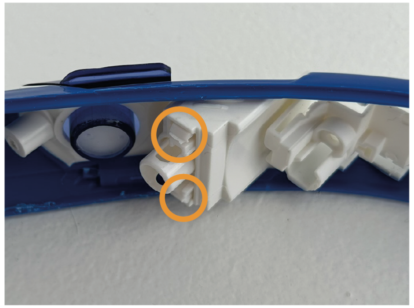
b: Clearance fit with the turn button perimeter



c: Transition (snap) fit with the top cover

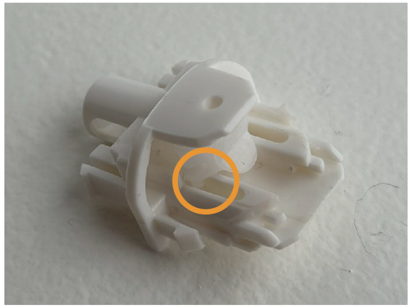


d, e: Transition fit and depth stop with the leaf spring

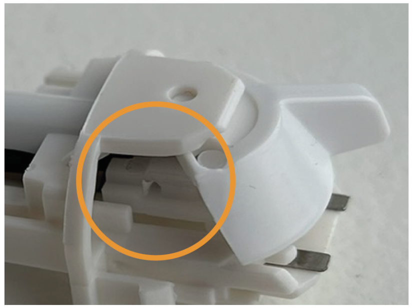


f: Transition (snap) fit at the bottom of the top shell

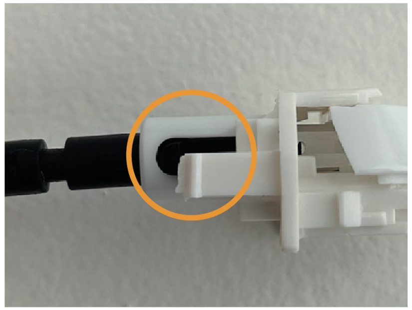
g, h, i: Clearance fit in the upper half of the top shell



j: Clearance fit with the slider



k: Height-restricted clearance fit with the slider and turn button



l, m: Clearance fit and rotation stop with the black shaft

Figure 124: The functional surfaces of the steam setter holder that show how it is coupled to its surrounding parts.

Ideation

Figure 125 shows the ideas that were generated for the redesign of the snap fits in the steam setting assembly.

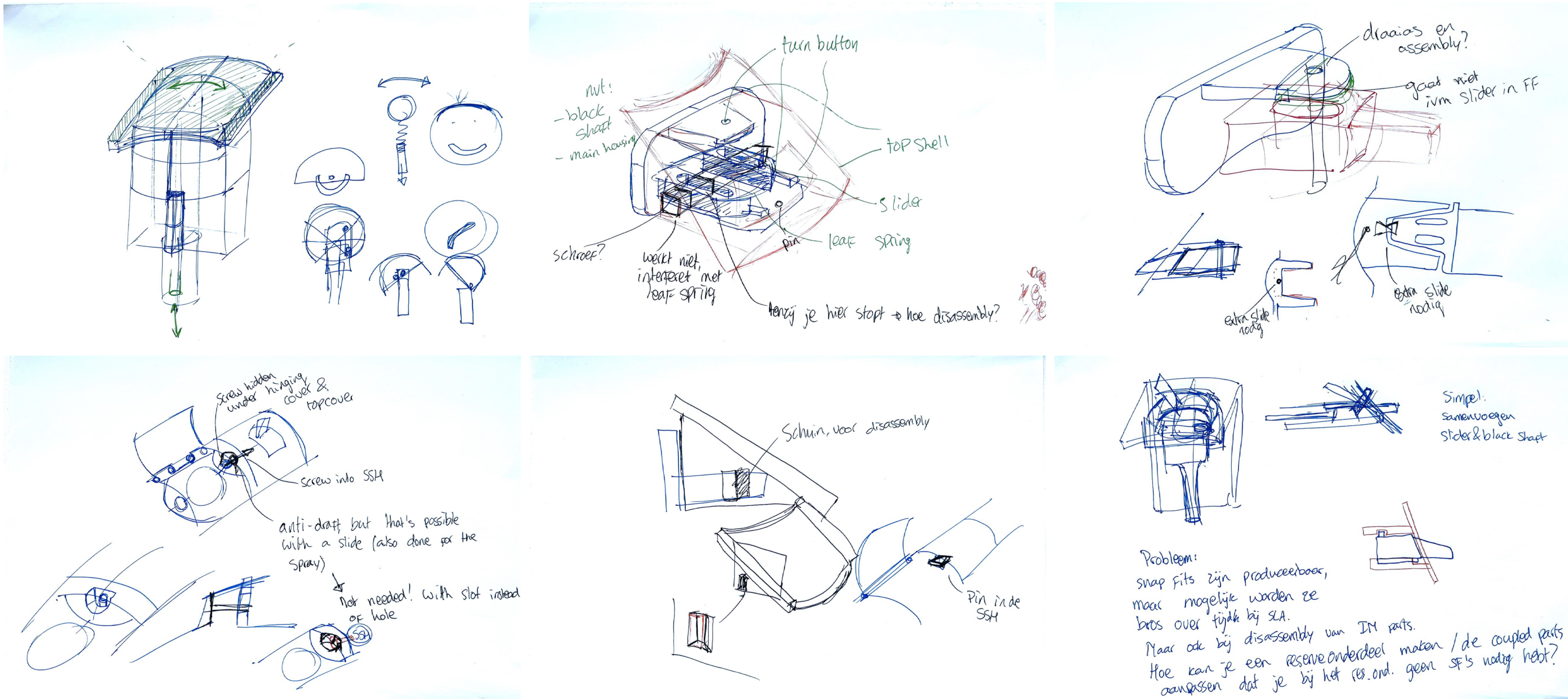


Figure 125: The generated ideas for a redesign of the steam setting mechanism.

FDM prototypes

Figure 126 shows the FDM prototypes that were made to validate the designs before waiting for the SLA parts to be manufactured. Minor adjustments were made to make the parts fit with the existing IM parts, such as the hole alignment.

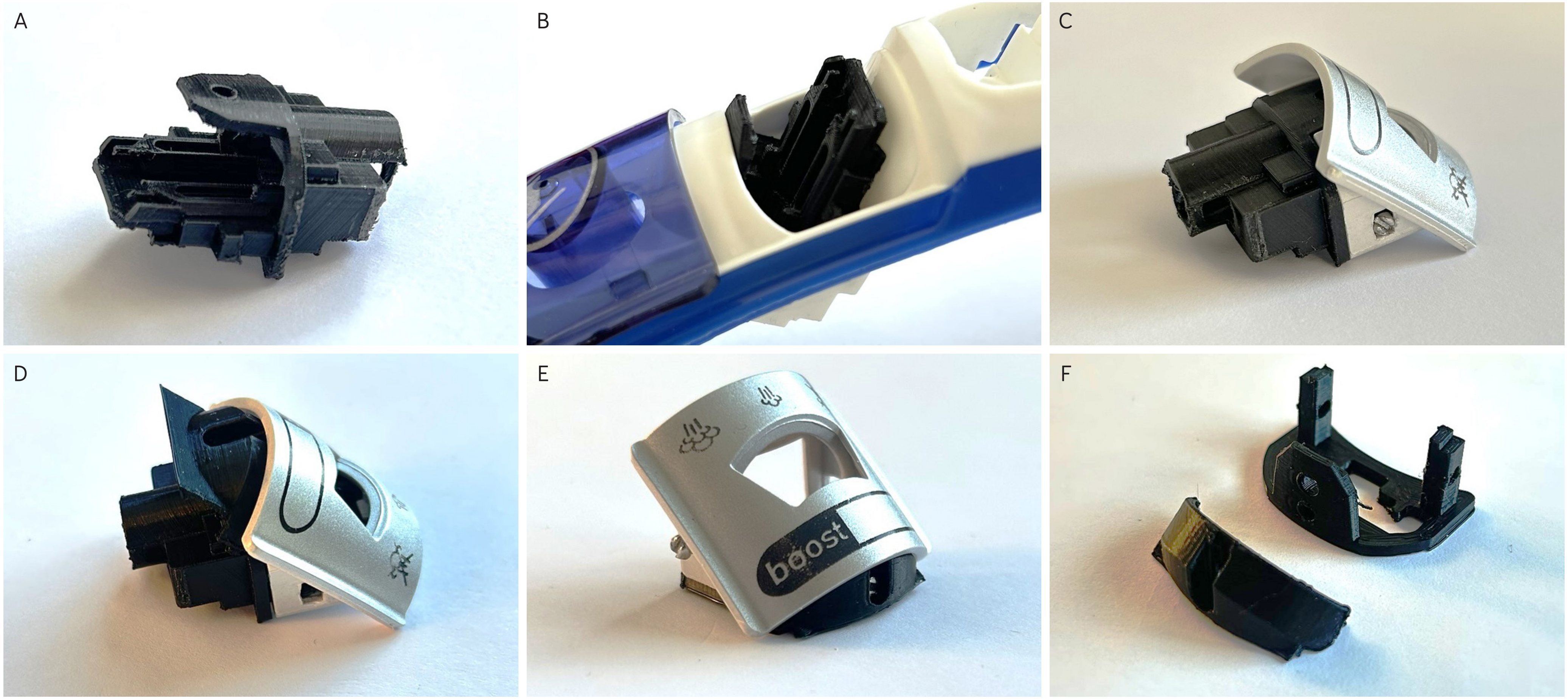


Figure 126: FDM prototypes of the design space of the steam setter holder (A, B), the new steam setter holder design (C) and the new top shell design (D, E, F).