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3D Printing for Repair: An Approach for Enhancing Repair

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

Keywords: 3D printing; repair; spare parts; framework; sustainability

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1. Introduction

Repair is an essential step in "slowing the flow" of products in a circular economy [1]. To promote reparability for ordinary consumers, the European Commission has implemented the first acts to ensure the availability of spare parts for consumer products such as dishwashers and fridges for a longer time period [2]. Increasing the availability of spare parts means that original equipment manufacturers (OEMs) need to find cost-effective ways to store spare parts for older products [3]. Instead of storage, an alternative solution would be to make the spare parts on demand: for example, through additive manufacturing [4,5]. Three-dimensional printing enables the continued availability of these parts long after storage becomes impractical [6], so, potentially, a manufacturer could support products indefinitely [7]. Additionally, 3D-printed spare parts could reduce repair times, labour costs, storage costs, material use, and transportation. In a study by Chekurov et al. [8], OEM participants estimated that between 2% and 75% of their companies' spare part libraries could be acceptably manufactured with 3D printing, with most answers between 5% and 10%. More parts can be expected to become feasible in the future with the rapid advance of 3D printing [9].

Current research mainly focuses on 3D printing spare parts by OEMs in industries such as aerospace, automotive, and machine tool production [10]. Topics include supply chain benefits and configuration, economic benefits, and sustainability benefits [11]. Other studies focus on the classification and selection of suitable spare parts [12]. Three-dimensional printing is good at producing complex geometry with high design flexibility and customisation [13]. A part can be tailored to its function with an optimal balance between strength and material use [14], which means the part can be improved compared to its original design [15]. Additionally, it gives the opportunity to modify and update the parts after the initial production has ceased [7,10,16].

Besides OEMs, 3D printing spare parts is also an interesting option for self-repair by consumers. Consumer interest in repair is increasing [17], but barriers to successful self-repair are the complicated repair process, expensive spare parts, and spare part unavailability [18]. The 3D printing of spare parts would enable repair where it normally is not intended by the manufacturer [19]. A study of the Open Repair Database (ORD) showed that 7.5–29% of non-repaired items in repair cafés could benefit from 3D-printed spare parts [20]. If OEMs do not provide the needed spare parts, customers might reverse-engineer the parts they need and share their instructions online [21].

However, the digitisation of spare parts for 3D printing is a challenge for both OEMs and consumers. Missing or insufficient availability of part data and 3D models can be significant obstacles in the digitisation process [8,12,22]. There is also a large number of spare parts that will only be feasible for 3D printing after significant redesign efforts [7,23], such as geometry or material optimisation [12,24]. As part properties are often dependent on the geometrical design, design rules for 3D printing are not easily generalised over different products and printing methods [24,25]. Instead, considerable skill is required to determine how part function and geometry are linked, so the question is how to support design engineers in the redesign process [26].

Specific guidance on redesigning existing parts for 3D printing is limited. There are numerous frameworks on design for additive manufacturing, such as [27–30]. However, none of these frameworks has been constructed with the repair of existing (spare) parts in mind. There are studies focused more specifically on using 3D printing in repair, such as [6,31–33]. The framework by Kim et al. [6] describes the partial repair of parts by comparing the damaged part against the whole parts and printing the difference. However, this assumes that a digital design of the file is already available. The methodology by Lindemann et al. [31] does offer support for redesigning an existing part for printing but represents the process as a black box. This makes it difficult to retrieve insights for process guidance. Park [32] and Terzioğlu et al. [33] present several consumer products repaired with 3D-printed parts in the context of consumer self-repair. However, these two studies mainly present the final results and not the process of developing the parts. Outside of the scientific literature, there are a few guides that describe the process of 3D printing a spare part by consumers, such as the work by Lorenzen and Paape [34] and the master thesis by Beerkens [35].

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

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

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

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

2. Materials and Methods

2.1. Establishing a Framework for 3DPfR

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

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

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

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

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

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

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

2.2. Identifying Factors for Successful Repair

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

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

The qualitative dataset was coded independently by two people using a predetermined coding table. The coding table was constructed by defining when a certain process step or part requirement can be considered applicable. For process steps, this included definitions of whether it was performed correctly or incorrectly; for part requirements, this included definitions of when a part met the requirement. Appendix A lists the definitions of correct/incorrect for each process step and applicable/not applicable for each part requirement. The student presentation slides were then coded by comparing the data to the definitions of the coding table and selecting the corresponding code. Table 1 presents a summary of the coding table; the full coding table with explanations and examples can be found in Appendix A. The coding table was constructed before coding, but codes were adjusted and recoded where needed while coding. The coding agreement of the final coded dataset was 0.81 using Cohen's Kappa. For the final data analysis, one of the two coding datasets was chosen at random because of their close agreement.

Table 1. Summary of the coding table.

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

* A step was coded *not applicable* if it was not required or not possible in the repair case. For example, not all printed parts require post-processing.

The quantitative data analysis counted and graphed the relevant codes and interpreted the data by comparing numbers and Adjusted Wald confidence intervals. Codes can only occur once per case, so no adjustment for double-counting was needed. The data were graphed as bar charts with Adjusted Wald confidence intervals visualised as error bars. The Adjusted Wald confidence interval was chosen because it yields coverage probabilities close to nominal confidence levels, even for very small sample sizes [36]. All Adjusted Wald intervals were calculated at 95% confidence.

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

3. Results

3.1. The 3DPfR Framework

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

3.1.1. Literature Review

Figure 1 summarises the insights from the literature to formalise the 3D printing for repair (3DPfR) process for DIY repairers. The literature framework flowcharts are grouped per topic. Activities (flowchart boxes) on the same row are similar, whereas a gap indicates framework differences. If a framework was characterised as an iterative process, it is mentioned in the last row.

Selected Steps That Appeared in All Frameworks

Figure 1 shows that (almost) all frameworks considered in this literature review included some form of the following activities, which were thus selected as 3DPfR process steps: *analyse part and product*, *design synthesis* and *digitise part*, *prepare print* and *print part*, *repair*, *test part performance*, and *iterate.*

Analyse part and product studies the part and product in detail to come to the part requirements. Analysis of part topology (refers to how the part is connected within the product [28]), part geometry (refers to what the part itself looks like [28]), and part functionality [28,35] shows what part features and functions are critical, and what can be simplified [29,35]. Reverse engineering the original part can restructure the initial design intentions. This helps to find the best design and manufacturing approach and to indicate process difficulty [35].

Design synthesis and *digitise part*, respectively, ideate and model a part that meets the part requirements from the analysis. A successful design cycle is supported by and implements other phases of the design cycle [37]. Idea generation involves creative thinking to come up with suitable repair solutions. The repairer needs to make aesthetic and structural decisions while considering the reproducibility of the repair [38]. Additionally, the part design should be adjusted and optimised for 3D printing. Parts can be combined or segmented or simplified to an easier geometry with the same function [29]. For large or complex parts, only the defective segment could be printed [34].

Prepare print and *print part* turn the digital model into a physical object through 3D printing. The (digital) preparation steps for this include exporting the CAD file as an STL file, which can be sliced to generate printer toolpaths [28,39]. Part slicing can be influenced by printer settings, such as support, infill, layer thickness, wall thickness, and bed adhesion. Printer settings influence part functionality and aesthetics, as well as printing ease, printing time, and material use [39].

Repair restores the product to a functional state using the manufactured part. This involves component repair/replacement, which leads to an altered functional product [40]. It can also be seen as an implementation phase that implements the developed decisions and solutions to restore product functionality [38].

Test part performance finds out how the printed part compares against the set design requirements. There will always be differences between the expected and desired properties. Judging whether these differences are acceptable is difficult, as there are a large number of properties involved [37]. Testing the part can include checking print errors and part appearance [39], confirming correct part dimensions, and proof testing (destructive or non-destructive) the mechanical response [28].

Iterate is an inherent step in any design process [37]. Besides the design process, iteration could also take place in the fault diagnosis [40]. Through these iterative feedback loops, design decisions can be reviewed as the design progresses [28].

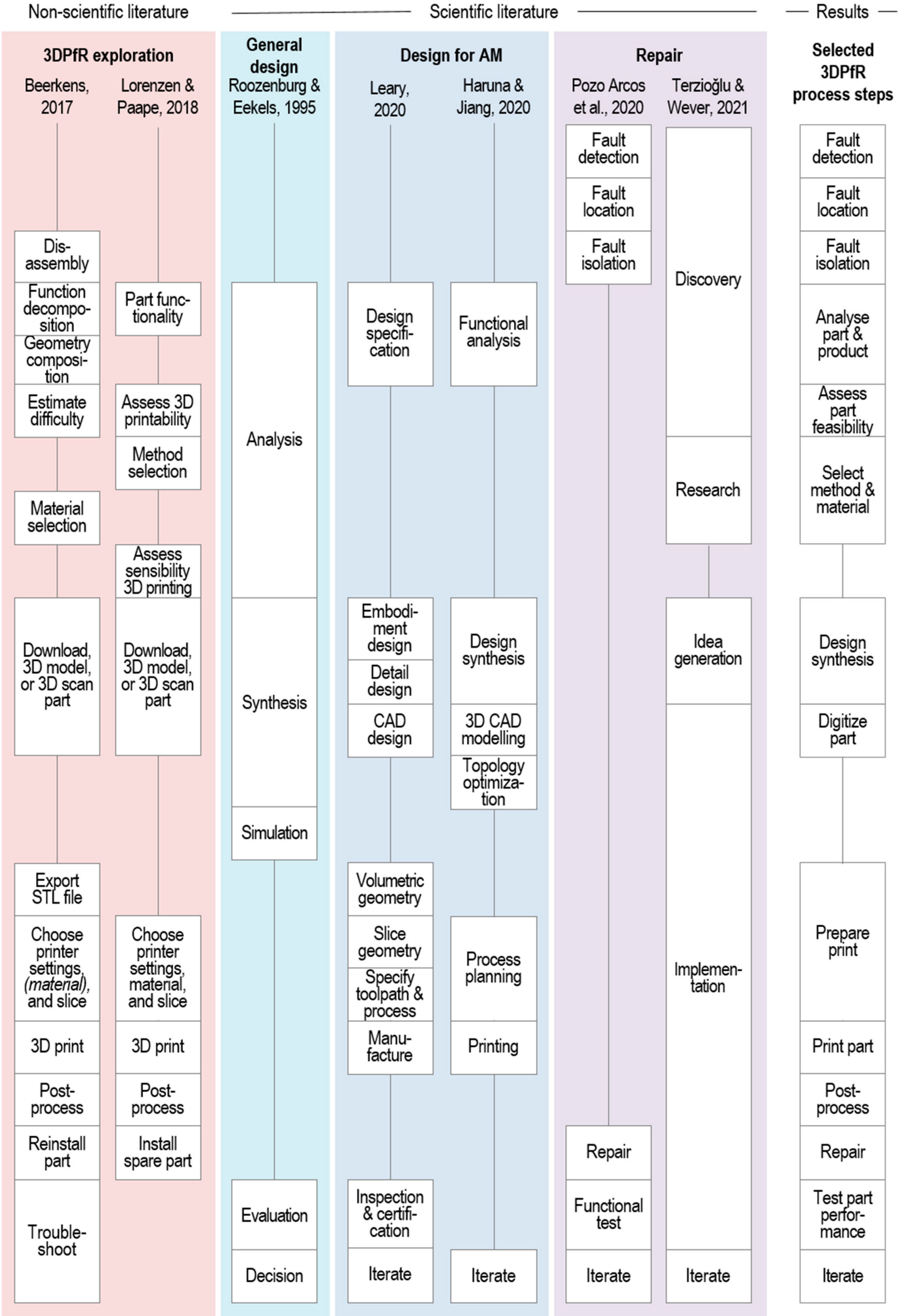


Figure 1. Overview of relevant frameworks from the literature study and the selected 3DPfR steps [28,29,34,35,37,38,40].

Selected Steps That Appeared in Some Frameworks

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

Fault diagnosis is an essential repair step to find the broken part. Fault diagnosis can be divided into *fault detection*, *fault location*, and *fault isolation* [40]. In these steps, the symptoms, causes of failure, and corrective actions are studied and tested to come to the repair diagnosis. Reverse engineering how the product was used and damaged helps to prevent the same damage in the repair redesign [38].

Assess part feasibility considers both the technical and practical feasibility of successfully 3D printing the part, such as 3D file availability and the technical limits of 3D printing [34]. Part feasibility should consider the required time, amount of design work, economic effort, resource consumption, environmental impacts, perceived value, and emotional meaning [34,38,41]. Complex, challenging, or incomplete parts will make the redesign process more difficult and time-consuming [41]. For non-feasible parts, alternative approaches might be considered, such as using another manufacturing method [34].

Select method and material should take place early in the process, as it will influence the design process. Various 3D printing processes have different construction methods, which will influence the design possibilities [34]. Additionally, material choice greatly influences the part's performance and functioning [35].

Post-processing is often needed to meet functional and aesthetic part requirements. It includes removing support structures, joining segmented part sections (plugging, screwing, clipping, or glueing), drilling, milling, or lubrication [34]. Surface finish and aesthetics can be adjusted through, for example, sanding, polishing, coating, or painting [39].

Steps That Were Not Selected

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

Assess 3D printing sensibility [34] was excluded because the difference between feasibility and sensibility is too minor. Sensibility determines whether it would be better to buy the original spare part, buy a new product, or use a different manufacturing method [34]. However, most feasibility assessments will include sensibility aspects, so it does not make sense to highlight it as a separate step. Instead, it is marked as an additional insight for shaping the *assess part feasibility* step.

Topology optimisation [29] was excluded because this is generally not accessible for DIY repair. It assumes an advanced additive manufacturing (AM) process, high skill level, and high-end equipment. Additionally, these methods focus on general AM performance, rather than repair.

Simulation [37] was excluded because the availability of 3D printing simulation tools for consumers is currently limited. Furthermore, 3D printing has a short lead time and high flexibility compared to traditional manufacturing. This makes it easier to test the printed part instead of predicting part behaviour through logical reasoning or model tests.

Certification [28] was excluded because the certification of 3D printing is almost non-existing at the moment. Additionally, within non-licensed repair, consumers will not be able to certify the parts themselves.

Additional Insights

Three-dimensional printing should not be the first step in replacing a broken part. If there are already produced and affordable spare parts available, it makes more sense to use those instead Only if the replacement part is not available or disproportionately expensive, it becomes interesting to 3D print it [34]. It is also good to consider the longevity and reparability of the repaired product. The repair might strengthen the product or make it more susceptible to damage. Similarly, the repair solution can make product repair easier or more difficult and can also impact the (perceived) product value and aesthetics [38].

3.1.2. Experimental Study

The selected process steps from the literature review were tested in the experimental study. Table 2 shows the process results, and Figure 2 shows the original part and redesigned 3D-printed part for all repair cases. Two out of three part replacements succeeded and one failed, which matched our initial feasibility expectation.

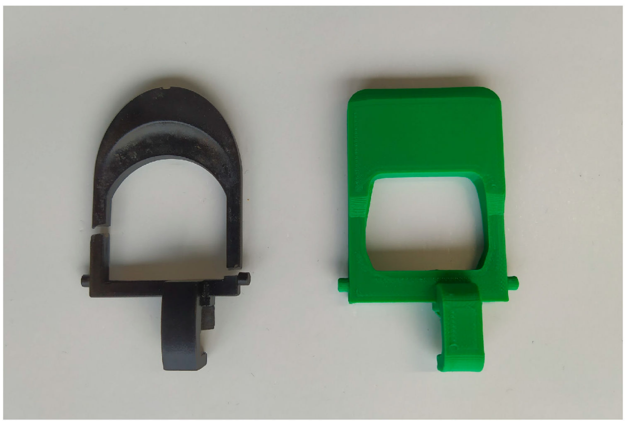
Table 2. Repair case results.

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

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

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

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



(a)

(b)

Figure 2. *Cont.*

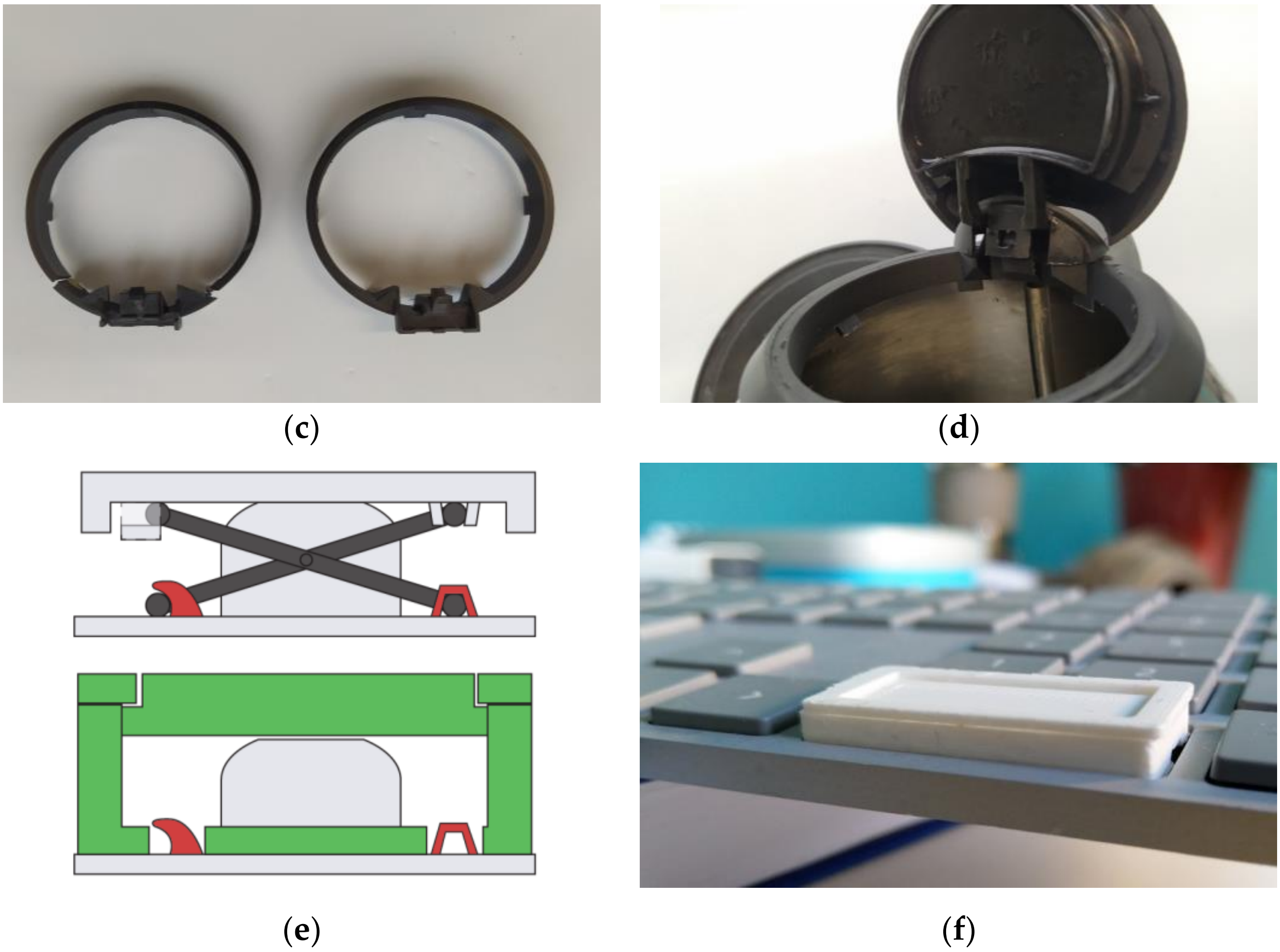


Figure 2. Comparison of the original and 3D-printed case study parts: (**a**) original kettle switch (left) and 3D-printed redesign (right); (**b**) 3D-printed kettle switch installed in kettle; (**c**) original kettle locking ring (left) and 3D-printed redesign (right); (**d**) 3D-printed kettle locking ring installed in kettle; (**e**) the original keyboard key scissor mechanism (above) with broken attachments (red), and the redesign (below) with 3D-printed parts (green); (**f**) 3D-printed parts on the keyboard.

Process Changes

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

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

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

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

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

Process Validation and Clarification

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

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

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

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

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

3.2. Factors for Successful Repair

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

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

3.2.1. Previous Experience

Figure 3 shows the influence of previous experience on the repair result.

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

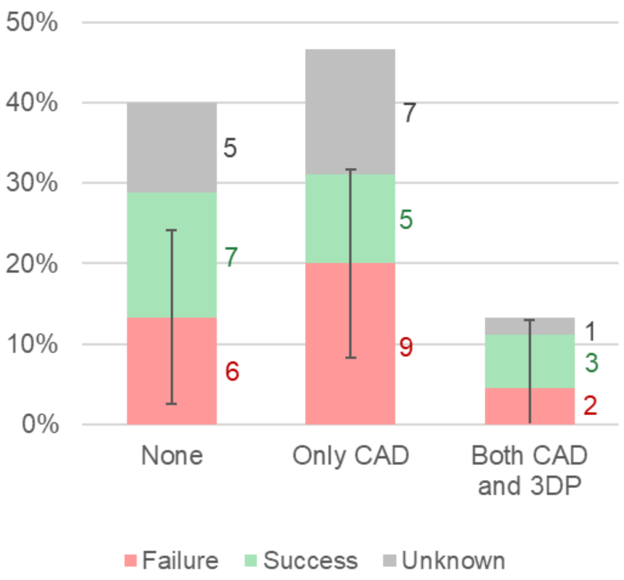


Figure 3. Repair result for each level of previous experience.

3.2.2. Process Implementation

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

Overall Process Implementation

Figure 4 shows whether each process step from the 3DPfR framework was incorrectly performed, correctly performed, or not applicable for a particular repair case. In Appendix B, a complete overview of the more granular process steps can be found.

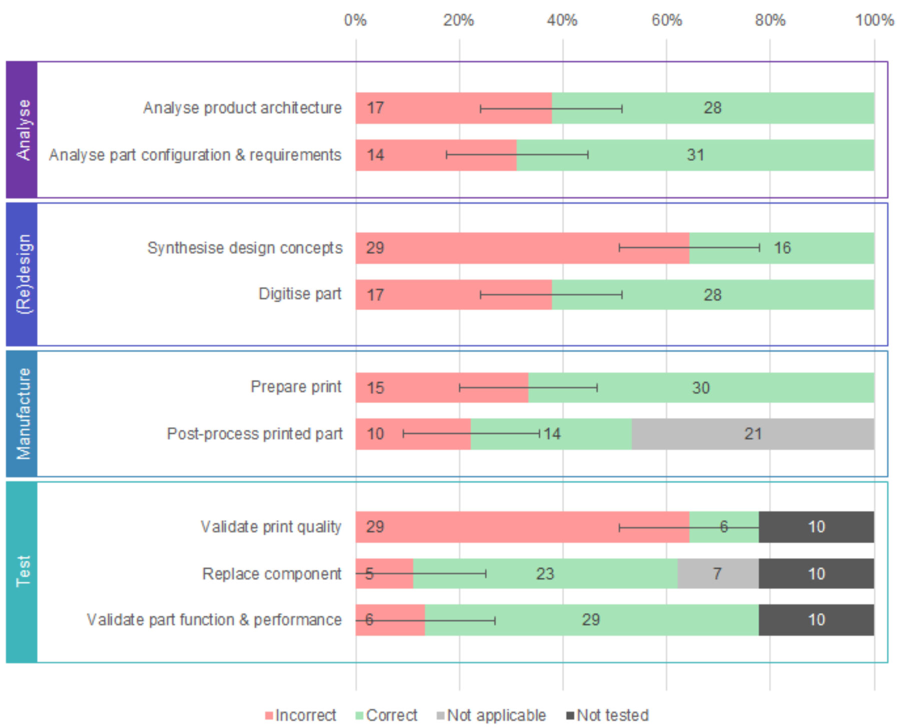


Figure 4. 3DPfR process steps (per phase) that were performed incorrectly, performed correctly, or not applicable for a particular repair case.

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

Analyse Phase

Figure 5 shows whether each *analyse* process step was incorrectly performed, correctly performed, or not applicable in relation to the repair result. The failed repairs are listed on the left, and the successful repairs are on the right.

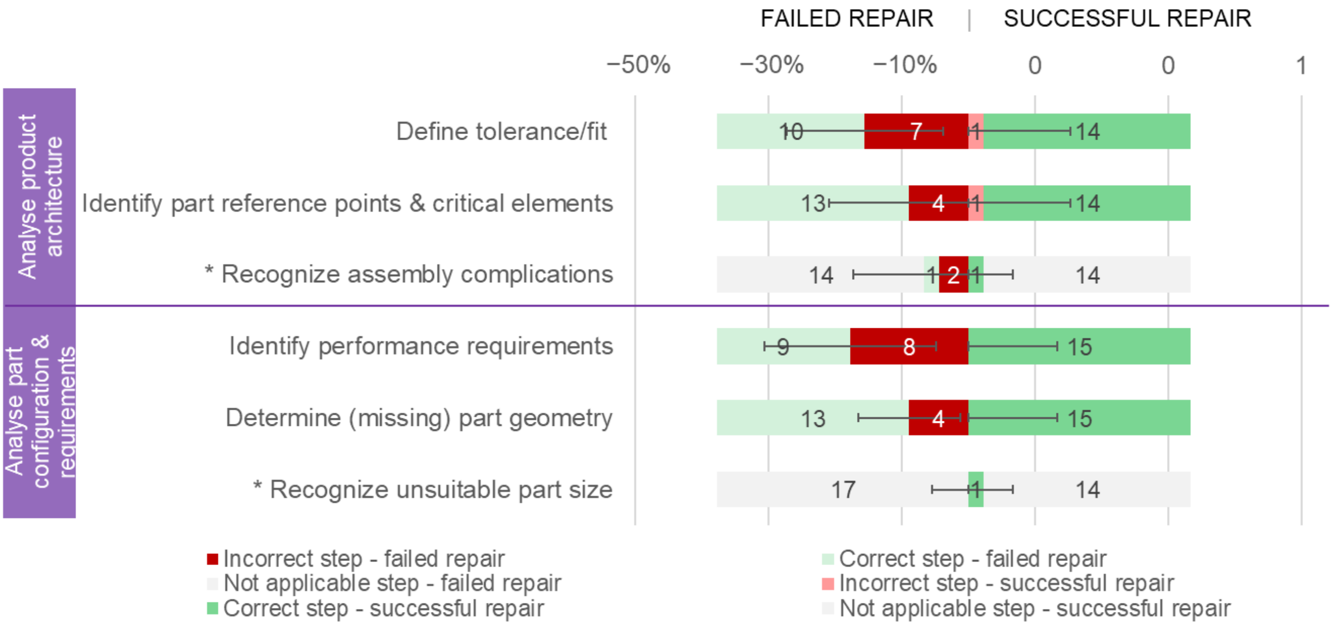


Figure 5. Effect of analysis process step correctness on the repair result. Cases with an unknown repair result have been omitted from this graph. * Process step not applicable to all repair cases.

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

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

(Re)design Phase

Figure 6 shows whether each *(re)design* process step was incorrectly performed, correctly performed, or not applicable in relation to the repair result. The failed repairs are listed on the left, and the successful repairs are on the right.

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

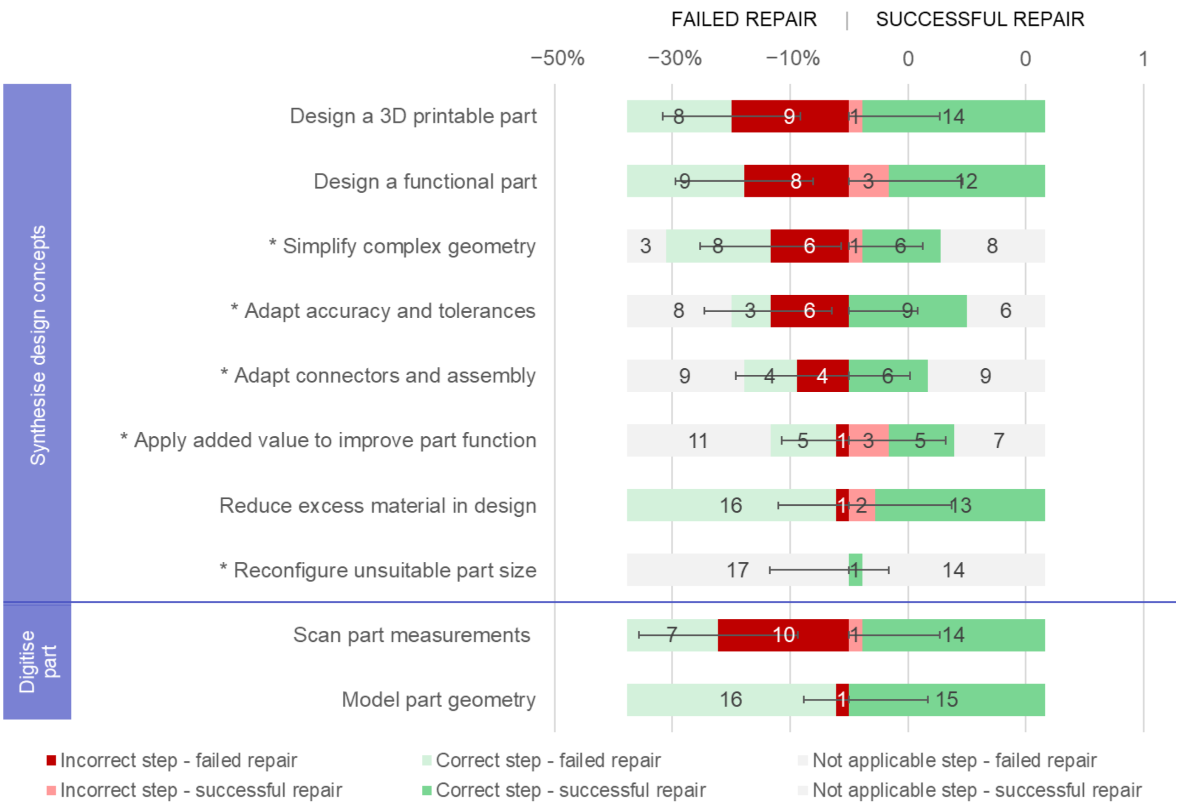


Figure 6. Effect of (re)design process step correctness on the repair result. Cases with an unknown repair result have been omitted from this graph. * Process step not applicable to all repair cases.

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

Manufacture Phase

Figure 7 shows whether each *manufacture* process step was incorrectly performed, correctly performed, or not applicable in relation to the repair result. The failed repairs are listed on the left, and the successful repairs are on the right.

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

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

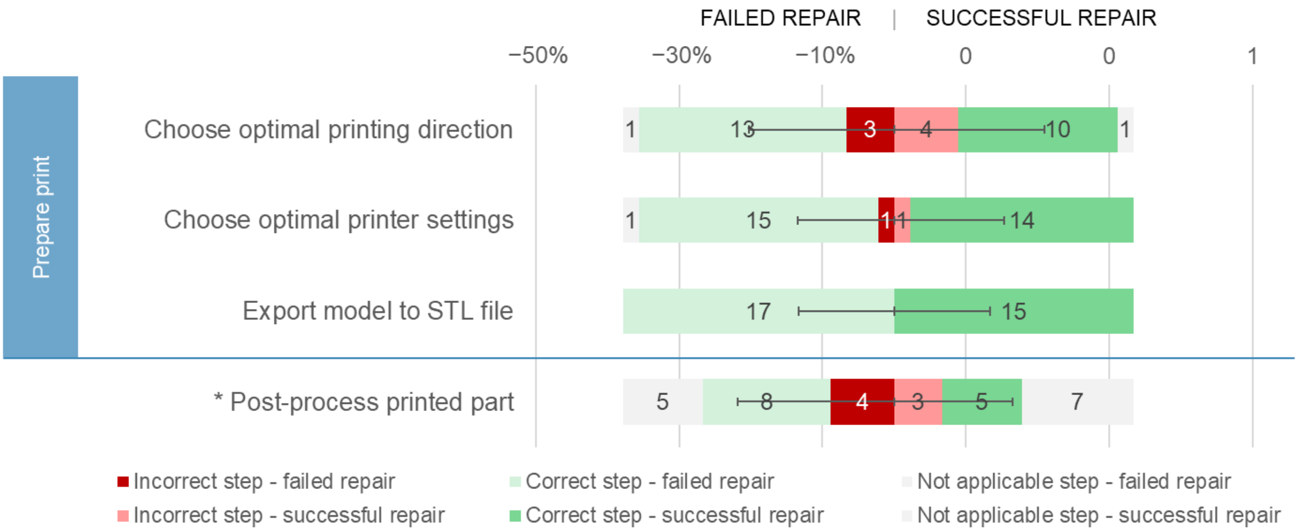


Figure 7. Effect of manufacturing process step correctness on the repair result. Cases with an unknown repair result have been omitted from this graph. * Process step not applicable to all repair cases.

3.2.3. Part Complexity

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

Part Geometry Completeness

Figure 8 shows the effect of part geometry completeness on the repair result. For a *complete* part, all the part geometry is known, although the part does not have to be intact. For an *incomplete* part, either part geometry has gone missing or has been deformed.

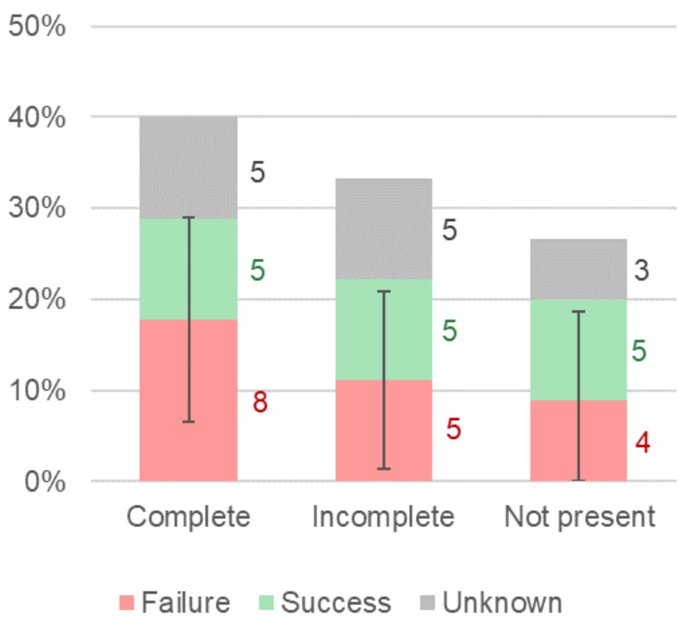


Figure 8. Effect of part geometry completeness on repair result.

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

Part Requirements

Figure 9 shows which part requirements were found in parts that participants selected as a repair case during the practicum.

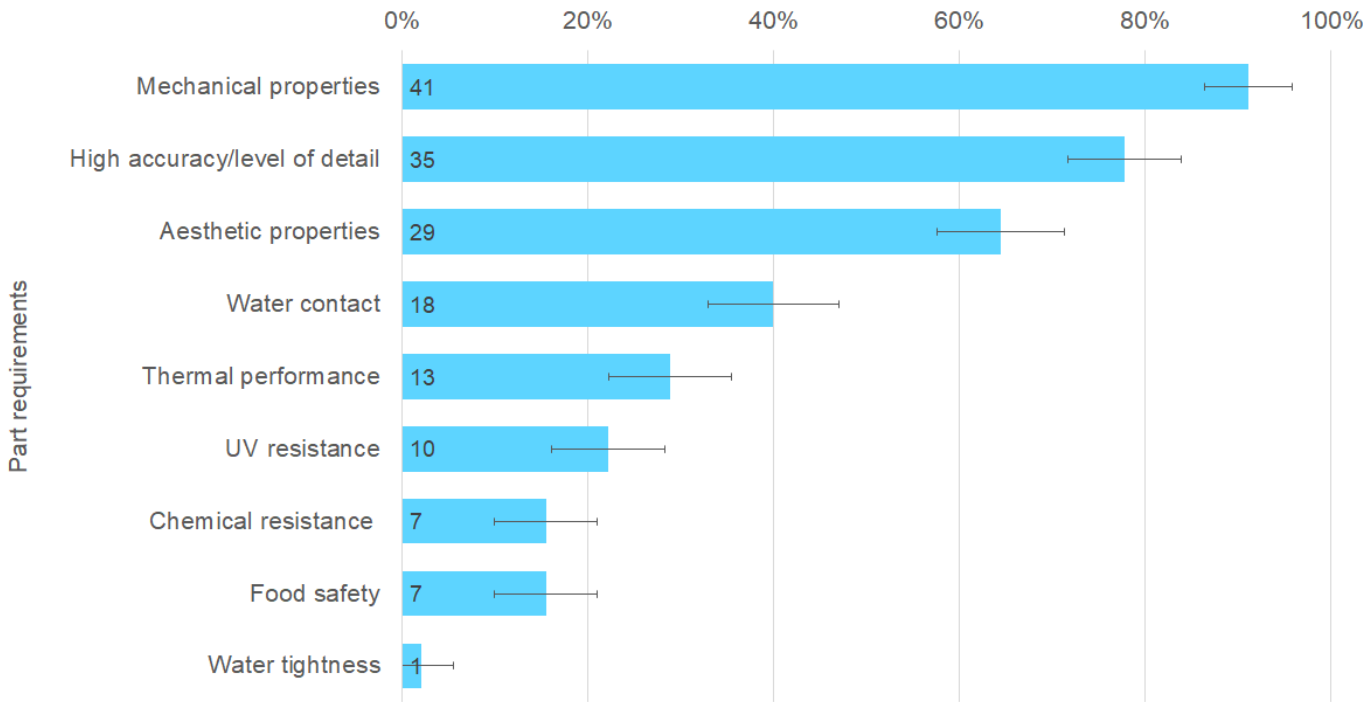


Figure 9. The types and frequency of part requirements in the parts used in this study.

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

Figure 10 considers the extent of the part requirements and shows the effect of demanding part requirements on the repair result. Parts with demanding part requirements are expected to require adaptation of the part design in order to be successful. Only the demanding part requirements were considered when studying the impact of part requirements on the repair result.

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

Part food safety required was never met, as it is very difficult to achieve food safety with FDM printing [42]. Additionally, if there is no optimal printing direction for the part, it is very likely that the repair will fail. Optimisation of the printing direction refers either to part performance, such as optimising mechanical strength, or the printing process, such as optimising printing time, the amount of support material, and post-processing time. This optimisation is not determined by a specific geometry feature or part requirement, but rather by the way in which geometry features and/or part requirements are combined. For all other demanding part requirements, there does not seem to be a significant effect on the repair result.

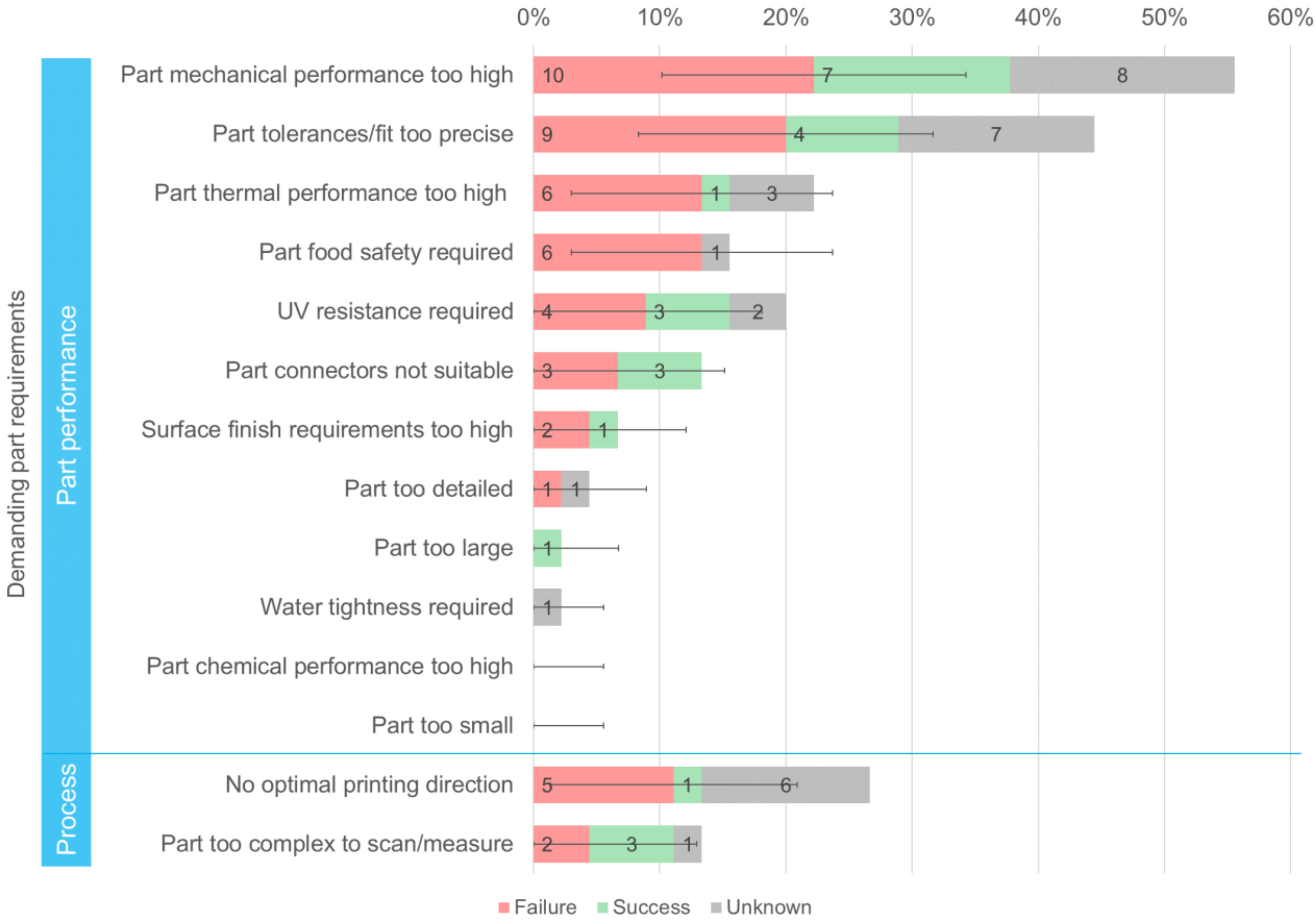


Figure 10. Effect of demanding part requirements on the repair result.

Overall Part Suitability

Figure 11 shows the relation between overall part suitability and the repair result. Part suitability was determined using the number of unsuitable part requirements. A part was deemed unsuitable if it had over five demanding part requirements, or if (the extent of) the demanding part requirement was virtually impossible to overcome with desktop 3D printing.

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

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

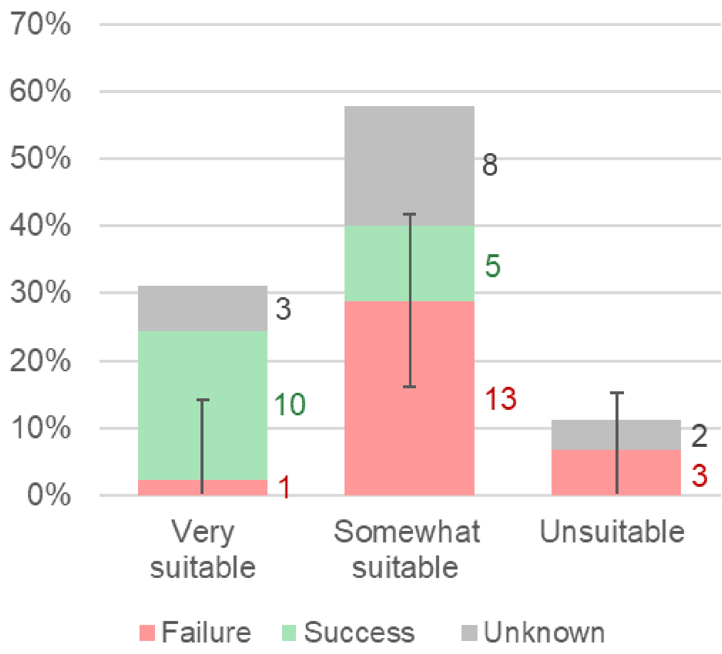


Figure 11. Effect of part suitability on the repair result.

4. Discussion

4.1. 3DPfR Framework

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

4.1.1. Finalising the Framework

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

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

By restructuring the literature process steps, as described above, we came to the final iteration of the 3D printing for repair framework as shown in Figure 12.

A successful process depends not only on process implementation, but also on previous experience, part characteristics, the (available) printing method, equipment and materials, and time spent. Analysing the relation between these factors and the repair result will show what the most likely failure points are. Most of these factors are addressed in RQ2. Fault diagnosis was not explored further as it is not closely integrated into the 3DPfR process. The steps *select method and material*, *print part*, and *iterate* were not explored further due to time and equipment constraints; see Section 4.3, Limitations and Recommendations.

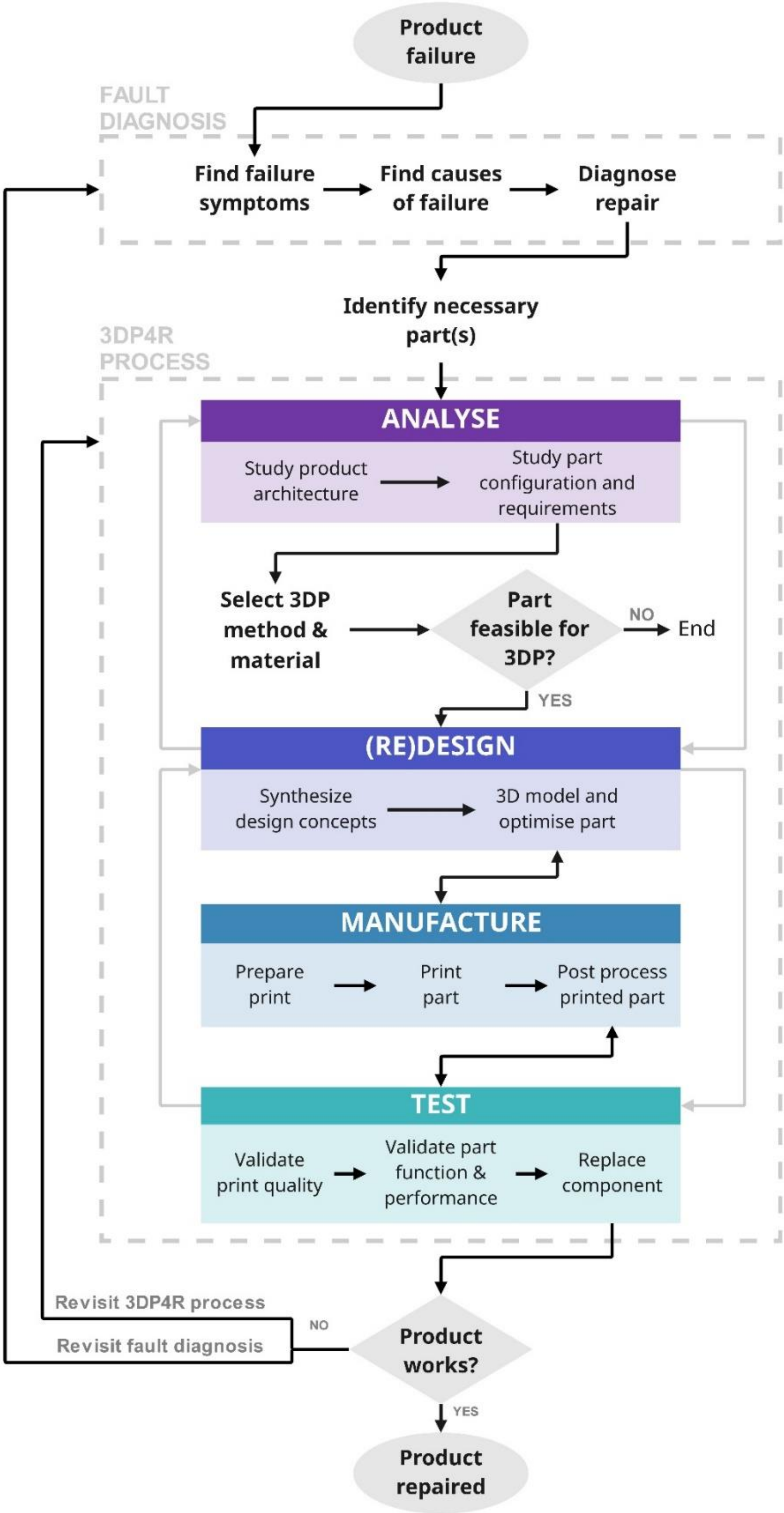


Figure 12. 3DPfR framework.

4.1.2. Complications in Framework Application

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

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

4.2. Factors for Successful Repair

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

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

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

4.2.1. Previous Experience

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

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

4.2.2. Process Implementation

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

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

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

4.2.3. Part Complexity

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

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

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

4.3. Limitations and Recommendations for Future Research

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

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

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

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

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

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

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

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

5. Conclusions

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

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

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

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

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Institutional Review Board Statement: This study was exempt from Institutional Review Board conditions because no data were collected on participants, only on 3D printing for repair.

Informed Consent Statement: Participant consent was waived as the activities performed were part of the practicum, not special to this research.

Data Availability Statement: The data presented in this study are openly available in 4TU.ResearchData at https://doi.org/10.4121/22226677.v1.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

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

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

Code	Options	Definition	Examples from Dataset
Overall Repair Characterisation			
Repair result	Failure	The manufactured part is installed but the product function is not back, or the part does not fit properly.	A 3D-printed keyboard stand clip was too small to fit in the keyboard, so it did not work.
	Success	The part fits and the intended part functionality is restored.	The back cover of an alarm clock was successfully replaced with a 3D-printed part.
	Unknown	Machine error, incomplete testing phase, or otherwise insufficient information to judge the part fit and function.	Some users could not pick up their printed parts for testing as they were abroad/in different cities; for some parts, the printer ran out of filament.
Repair type	Repair	The repair focuses on restoring the original function of a broken part.	A washing machine button was replaced with a 3D-printed button with the same fit and function.
	Added value	The repair focuses on optimising the functionality of a non-broken part, or on repurposing a broken part.	A functioning Nintendo Switch joy-con rail was redesigned to make the controller more comfortable to hold.
	Both	The repair focuses on restoring the function of a broken part and on optimising/adding functionality/personalising the part compared to its original function.	A broken multimeter stand was replaced, and holes were added to the design to hold the probe cables.
Previous experience			
Previous experience	None	The participant mentions that they had not previously used CAD modelling and 3D printing, or expressed difficulty with these skills.	" … I had no prior experience with [modelling a 3D part], it was totally unfamiliar for me what I had to do"
	Only CAD	The participant mentions experience with CAD modelling.	" … I already had some experience with modelling … The 3D printing itself I had actually never done before"
	Both CAD and 3DP	The participant mentions experience with CAD modelling and 3D printing.	" … I have had the privilege to gain a lot of experience within prototyping and products design also based on FDM 3D printing … "
Process implementation			
Analyse process steps			

Table A1. *Cont.*

Code	Options	Definition	Examples from Dataset
Define tolerance/fit	Incorrect	The participant does not recognise how loose/tight the part should fit or does not pay attention to it.	One participant measured the part cavity and gave the part the same measurements, while the part should have a looser fit.
	Correct	The participant recognises how loose/tight the part should fit.	"Assemble type:—Loose fit" for a ring to hold a toilet seat in place.
Identify part reference points and critical elements	Incorrect	The identification of part reference points and critical elements is incomplete and/or incorrect.	A coffee pot lid did not take into account the reference to the coffee maker nozzle, and thus the coffee would not flow through.
	Correct	The identification of part reference points and critical elements is complete and correct.	A faucet knob was designed to match the existing male part of the faucet knob.
Recognise assembly complications	Incorrect	The fact that a part is difficult to assemble (either due to original design/assembly or because of 3D-printed part properties) is not recognised.	A screw thread of a cupboard leg was redesigned only because the participant could not model a screw thread, but the redesign still had the same issues (too delicate to be printed).
	Correct	The fact that a part is difficult to assemble (either due to original design/assembly or because of 3D-printed part properties) is recognised.	It was recognised that a 3D-printed closure hook for a panini maker could not snap into place like the original injection-moulded part did.
	Not applicable	There were no assembly complications.	A 3D-printed zipper pull could use the same assembly method as the original zipper pull.
Identify part performance requirements	Incorrect	The identified performance requirements are not logical and/or incomplete.	It was not recognised that a 3D-printed beer bottle opener would require great strength and stiffness.
	Correct	The identified performance requirements are logical and complete.	A monitor cable holder "needs to be flexible enough to clip around the pole".
Determine (missing) part geometry	Incorrect	The geometry of the part is determined incorrectly, or incorrect assumptions are made when constructing missing geometry.	It was not noticed that the walls of a lamp bracket were slanted instead of perpendicular.
	Correct	The geometry of the part is determined correctly, and correct assumptions are made when constructing missing geometry.	The geometry of a washing machine knob was completely reconstructed with the help of the internal geometry.
Recognise unsuitable part size	Incorrect	The fact that the part is too small or too large (see *part unsuitability types*) is not recognised.	*No example available.*
	Correct	The fact that the part is too small or too large (see *part unsuitability types*) is recognised.	It was recognised that the handle of a vacuum cleaner was too large to fit on the build plate.
	Not applicable	The part was a suitable size for (desktop FDM) 3D printing.	A cooking spoon handle was small enough to fit the build plate but larger than the printing resolution.
(Re)design process steps			

Table A1. *Cont.*

Code	Options	Definition	Examples from Dataset
Design a 3D-printable part	Incorrect	The part design does not meet the design rules for FDM printing by Hubs [43].	A cupboard leg could not be replaced because the designed screw mechanism could not be printed.
	Correct	The part design meets the design rules for FDM printing by Hubs [43].	A vacuum bag locking mechanism was redesigned into two parts so it could be 3D printed easier.
Design a functional part	Incorrect	The part design does not meet (or is not expected to meet) the performance requirements and function described in the analysis phase.	A bike light holder was redesigned so the lamp would not slip down the steering wheel, but the redesign still slipped down the steering wheel.
	Correct	The part design meets (or is expected to meet) the performance requirements and function described in the analysis phase.	A bike tire cover attachment has the right shape to clip both the luggage rack and the bike tire cover together.
Simplify complex geometry	Incorrect	The part simplification, if applied, hindered part printing and/or part function.	The attachment mechanism of a smartwatch bracelet was simplified, but it would not connect to the original mechanism of the watch itself.
	Correct	The part simplification, if applied, improved or did not hinder part printing and/or part function.	The battery cover of a mouse was redesigned to omit non-essential holes and curves.
	Not applicable	The part did not have any complex geometry that needed to be simplified, or it was feasible for 3D printing without simplification.	A T-shaped bike light post was simple enough to keep the original part design.
Adapt accuracy and tolerances	Incorrect	The part accuracy and tolerances needed to be adapted to fit 3D printing accuracy and tolerances, but this was performed insufficiently or incorrectly.	"I wanted to make it slightly bigger so [it] would not be too loose. But I overestimated the diameter which now result in some after processing."
	Correct	The part accuracy and tolerances needed to be adapted to fit 3D printing accuracy and tolerances, and this was performed correctly.	"In order to get a snug fit, I decreased the size I actually wanted in the CAD model by 0.5 mm . . . it was important that it was maybe a bit smaller than larger in order [to fit]"
	Not applicable	The part accuracy and tolerances were feasible for 3D printing and did not have to be adapted.	The fit of a teapot lid was loose enough that the accuracy and tolerances did not have to be adapted.
Adapt connectors and assembly	Incorrect	Unsuitable part connectors and assembly methods, if any, have not been adapted to make them suitable for 3D printing, or have been adapted in such a way that they negatively affect the part fit and/or function.	A complex hinge was changed into a spring, but the spring redesign would not have any flexibility, nor act as a spring.
	Correct	Unsuitable part connectors and assembly methods, if any, have been adapted to make them suitable for 3D printing, if needed.	A bike cover holder was designed that clamped over the cover, as the hole where the original bracket had been attached was broken beyond use.
	Not applicable	The part connectors and assembly were feasible for 3D printing and did not have to be adapted.	A coat hook used screw connections, which are also feasible in the 3D-printed part.

Table A1. *Cont.*

Code	Options	Definition	Examples from Dataset
Apply added value to improve part function	Incorrect	The added value in the design, if applied, hindered part printing and/or part function.	One participant wrote their name on their guitar knob, and the only possible printing direction to do this resulted in infill material in the knob hole, which was difficult to remove.
	Correct	The added value in the design, if applied, improved or did not hinder part printing and/or part function.	A teapot lid was redesigned to hold cookies.
	Not applicable	There was no added value applied in the redesign of the part; see repair type *repair.*	A washing machine button was replaced with a 3D-printed button with the same fit and function.
Reduce excess material in design	Incorrect	The same fit and function could have been achieved with less material without too much redesign effort (e.g., the part design is unnecessarily bulky).	A faucet knob was roughly 1.5 times the size of the original knob, while this is not required for either fit or function.
	Correct	The part design does not use more material than needed to achieve the required fit and function.	A teapot lid was simplified to a disk instead of a dome, which reduces the amount of used material.
Reconfigure unsuitable part size	Incorrect	An unsuitable part size (too large/too small) has not been reconfigured to make it suitable for 3D printing, or it has been reconfigured in a way that negatively affects the part fit and/or function.	*No example available.*
	Correct	An unsuitable part size has been reconfigured to make it suitable for 3D printing without negatively affecting the part fit and function.	The broken handle of a vacuum cleaner was repaired by a 3D-printed patch instead of replacing the whole handle.
	Not applicable	The part was a suitable size for (desktop FDM) 3D printing; see analysis step *recognise unsuitable part size—not applicable*.	A cooking spoon handle was small enough to fit the build plate but larger than the printing resolution.
Scan part measurements	Incorrect	Measurement equipment is used incorrectly and/or one or more of the part measurements are incorrect.	"Measuring round parts and the small fins on the spoon is very hard with only a ruler."
	Correct	Measurement equipment is used correctly, and all part measurements are correct.	A roller blinds connector was carefully measured, and all measurements were noted in a sketch.
Model part geometry	Incorrect	The 3D CAD model of the part has different measurements and/or scale compared to the scanned part measurements.	The lid for a blender was modelled/scaled incorrectly, and measured 2 cm instead of 20 cm.
	Correct	The 3D CAD model has the same measurements and scale as the scanned part measurements.	A 3D-printed dough hook "fitted perfectly and feels steady".
Manufacture process steps			

Table A1. *Cont.*

Code	Options	Definition	Examples from Dataset
Choose optimal printing direction	Incorrect	The printing direction (part printing direction) hinders the part structure/does not benefit any part section or generates unnecessary support material.	A washing machine button (rectangular) was printed standing upright, which makes it weaker and adds support material, while it could have been printed lying flat without support material.
	Correct	The printing direction benefits the part structure (as much as possible) and does not generate unnecessary support material.	A lid for a teapot was printed with the visible side up, so the rough surface left after post-processing would not be visible.
Choose optimal printer settings	Incorrect	The chosen printing settings compromise component functions or unnecessarily increase printing time and material use.	A washing machine button was printed with 100% infill, while this part does not require great strength.
	Correct	The chosen printing settings do not compromise component functions and do not unnecessarily increase printing time and material use.	The aeroplane model stand was printed with a "normal instead of fine profile" as it is a "fairly large part, so fine is not needed to save time".
Export model to STL file	Incorrect	Mistakes were made when exporting the 3D CAD model to STL, e.g., holes in the mesh or other issues described by Hubs [44].	*No example available.*
	Correct	The 3D CAD model from the CAD modelling software was correctly exported to an STL file format.	*All cases correctly exported the model to STL.*
Post-process print	Incorrect	The post-processing was not fully completed, damaged the part, or affected the part's function in some way.	A shaver attachment had narrow overhanging pins, which broke when the support underneath them was removed.
	Correct	The post-processing was completed and did not damage/affect the part.	The brim of a cooking spoon handle was correctly removed.
	Not applicable	Post-processing of the part was not required.	The aeroplane model stand was printed without support, so no post-processing was required.
Test process steps			
Not tested		The testing phase was not conducted or completed.	"Could not test the part since I was not in Delft".
Validate print quality	Incorrect	Printing defects [45] that affect part fit and/or function are not noticed, and/or the printed part weight is compared to something other than the slicer estimate (comparing the weight of the printed part to the slicer estimate can help to judge printer performance. If the actual weight is a lot lower than the estimated weight, this can indicate printing problems such as under-extrusion).	A number of people compared the weight of the printed part to the original part, which does not say anything about under-extrusion and print quality.
	Correct	Printing defects are noted, and the printed part weight is compared to the slicer estimate.	"Right side had a printing artefact where it was thicker".

Table A1. *Cont.*

Code	Options	Definition	Examples from Dataset
Replace component	Incorrect	The part was not replaced in the product, or it was installed in the wrong place and/or in any other way that affected part fit and/or function.	A pineapple cutter slicer blade was installed at the wrong end of the cutter.
	Correct	The part was replaced at the right location in the right order with the right connectors.	The dust bag locking mechanism was installed in the right order to hold the dust bag in place.
	Not applicable	The part could not be replaced in the product due to other incorrect steps (e.g., incorrect measurements).	A smartwatch bracelet half could not be reassembled due to incorrect measurements and incorrect redesign of the attachment mechanism.
Test setup suitable	Incorrect	The test setup is not suitable to test the part as it is not similar enough to simulate use of the part.	Attaching a bike light to a candelabra and shaking it to simulate use of the bike light on a bike.
	Correct	The test setup tests the right part behaviour in the original setup or a correct simulation of the original product.	A 3D-printed cooking spatula connector was submerged in boiling water to test the thermal performance.
Iterate (optional, added after numerous participants voluntarily gave their redesign insights)	Incorrect	The redesign actions offered are not likely to solve the issues with the part fit and/or function.	The proposed redesign iteration for a bottle opener was to change the measurements, while it broke because the mechanical requirements were too high.
	Correct	The offered redesign actions are likely to solve the issues with the part fit and/or function.	The redesign for a coffee pot lid did not work because it did not connect well to the coffee maker, and the proposed redesign was to take this element into account in the next iteration.
	Not mentioned	No redesign insights were mentioned.	-
Part complexity			
Part completeness	Complete	The original part was intact, or a broken part had no missing pieces, or geometry could be copied of identical parts.	A missing guitar tuning knob could be modelled by looking at the knobs that were still present.
	Incomplete	The original part had partially missing or deformed geometry.	The mounting bracket of a lamp had pieces broken off that were missing.
	Not present	The original part was not available.	The back cover of the alarm clock was missing.
Part requirements			
Mechanical properties (force/flexibility/ abrasion)	Yes/No	The part requires mechanical performance to fit and function, such as strength, stiffness, bending, torsion, flexibility, elasticity, and abrasion.	A (metal) bread maker dough hook required large strength and stiffness to withstand the forces applied to it while kneading the dough.
High accuracy/level of detail	Yes/No	The part requires a high manufacturing accuracy and/or level of detail to fit and function.	An aeroplane model stand required higher accuracy to ensure the model aeroplane clicks in tightly.
Aesthetic (surface quality, colour)	Yes/No	The part is visible during use, and/or requires aesthetic properties to fit and function (e.g., smooth surface required).	The aesthetic of a desk lamp was the reason to repair it, so the 3D-printed part should not interfere with this aesthetic.

Table A1. *Cont.*

Code	Options	Definition	Examples from Dataset
Water contact	Yes/No	The part requires the ability to withstand water contact in order to fit and function.	A bike light holder comes into contact with water if the bike stands outside when it rains.
Thermal performance	Yes/No	The part needs to withstand a certain temperature to fit and function.	A teapot lid comes into contact with hot steam.
UV resistance	Yes/No	The part is used in a place where it is exposed to sunlight (e.g., behind a window, outside, in a car).	A bike light holder comes into contact with UV light as bikes are used outside in the sun.
Chemical resistance	Yes/No	The part needs to withstand certain chemicals in order to fit and function.	A toilet seat part comes into contact with the chemicals used in household cleaning agents.
Food safety	Yes/No	The part comes into contact with food.	A teapot lid comes into contact with the tea while pouring the tea.
Water tightness	Yes/No	The part needs to hold water without leaking for a longer time period.	A blender lid needs to be watertight so the blender contents do not seep through the lid.
Part unsuitability types			
Part mechanical performance too high	Yes/No	The required mechanical performance (e.g., strength, stiffness, bending, torsion, flexibility, elasticity, abrasion) is too high to be feasible with (desktop FDM) 3D printing.	The forces on the dough hook of a bread maker are very likely to be too high to replicate with 3D printing.
Part tolerances/fit too precise	Yes/No	The required part tolerance/fit is too high to be feasible with (desktop FDM) 3D printing.	The precision required for the attachment mechanism of a smartwatch bracelet is too high to replicate with 3D printing.
Part thermal performance too high	Yes/No	The required part temperature is higher than the service temperature of the used material; in this case, standard PLA.	The heat of the steam in the teapot is too hot for the teapot lid, which will likely soften and maybe deform over time.
Part food safety required	Yes/No	The part comes into contact with food.	A cooking spatula connector that connects the handle and spoon is likely to come into contact with the contents of the cooking pot.
UV resistance required	Yes/No	The part is mostly used in a place where it is exposed to sunlight (e.g., behind a window, outside, in a car).	A bike light holder comes into contact with UV light as bikes are used outside in the sun.
Part chemical performance too high	Yes/No	The part needs to withstand chemical compounds that the used material, in this case, standard PLA, cannot withstand, e.g., antifreeze, acetone, strong acids [46].	*PLA is likely to withstand all the (common household) chemical compounds that the case study parts will encounter* [46].

Table A1. *Cont.*

Code	Options	Definition	Examples from Dataset
Part connectors not suitable (Even though part connector requirements rely on other part requirements (e.g., snap fits require flexibility), it was chosen to make this a different requirement as it is (almost always) located locally and only required during assembly (not during normal use)	Yes/No	The part connectors require properties that are difficult to achieve with 3D printing, e.g., snap fits or screw thread.	The back plate of an alarm clock requires a click mechanism that needs to flex considerably, which will be challenging to achieve with 3D printing.
Surface finish requirements too high	Yes/No	A very smooth surface is required for the part to fit and function correctly.	The lid of a coffee pot requires a smooth surface on both sides. This is difficult to achieve, as one side needs support, which leaves a rough surface.
Part too detailed	Yes/No	The part requires geometry that cannot be 3D printed as it is too thin/small/etc. [43]	A shaver attachment requires very small and thin prongs, which are likely to fail during printing/post-processing.
Part too large	Yes/No	The part was larger than the average build plate of desktop FDM printers (200 × 200 × 200).	The handle of the vacuum cleaner was larger than the print bed.
Part too small	Yes/No	The part dimensions for functional elements were smaller than the average printing accuracy (± 0.3 mm).	*No example available.*
Water tightness required	Yes/No	The part needs to hold water without leaking for a longer time period.	A blender lid needs to be watertight, so the blender contents do not seep through the lid.
No optimal printing direction	Yes/No	There is no printing direction that does not negatively affect the part fit, part function, printing time, and/or material use.	A phone stand for a bike mount had perpendicular overhangs in all directions, and the printing direction with the least support weakens the main part's body strength.

Appendix B

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

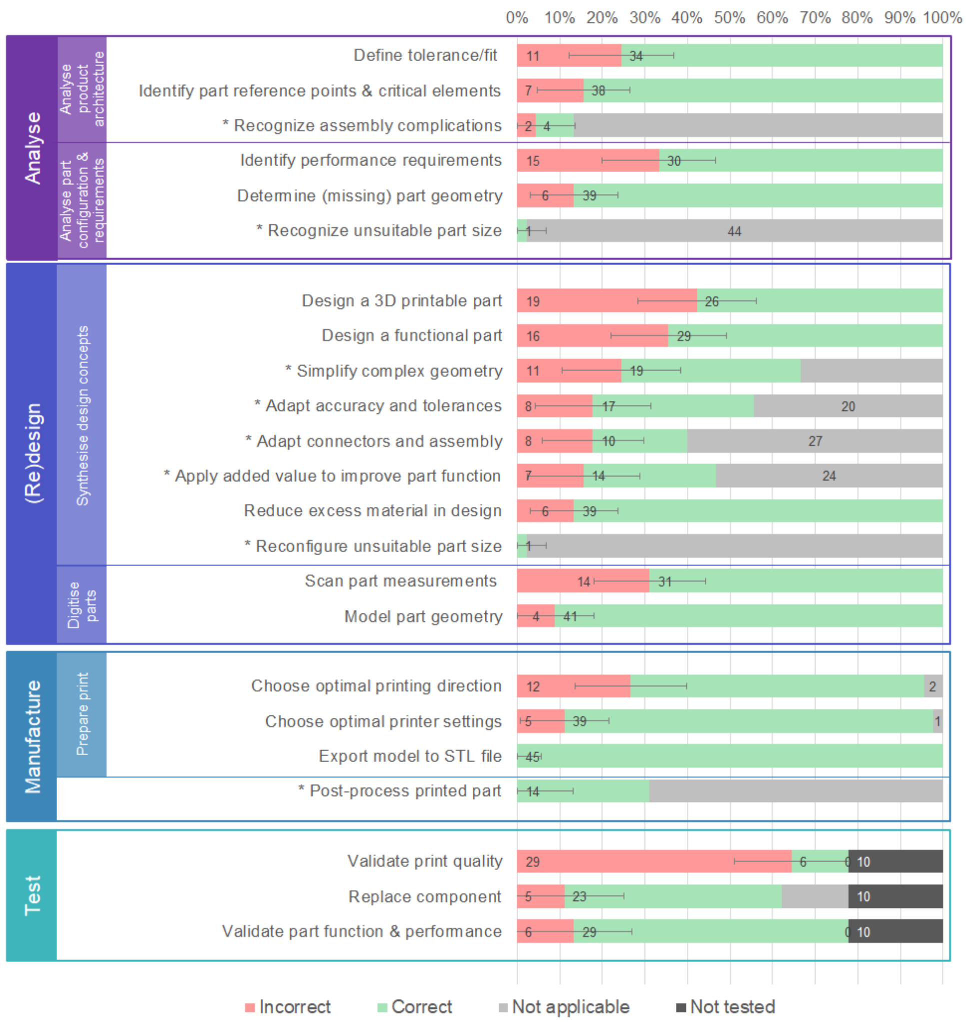

Figure A1. Full overview of all granulated process steps. * Process step not applicable to all repair cases.

Overall, the most common incorrect steps were:

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

The most common correct steps were:

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

References

1. Cooper, T. *The Circular Economy in the European Union*; Springer International Publishing: Cham, Switzerland, 2020; ISBN 9783030502393.
2. Šajn, N. *Right to Repair*; 2022. Available online: https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/698869/EPRS_BRI(2022)698869_EN.pdf (accessed on 18 March 2022).
3. Svensson-Hoglund, S.; Richter, J.L.; Maitre-Ekern, E.; Russell, J.D.; Pihlajarinne, T.; Dalhammar, C. Barriers, Enablers and Market Governance: A Review of the Policy Landscape for Repair of Consumer Electronics in the EU and the U.S. *J. Clean. Prod.* **2021**, *288*, 125488. [CrossRef]
4. Pérès, F.; Noyes, D. Envisioning E-Logistics Developments: Making Spare Parts in Situ and on Demand. State of the Art and Guidelines for Future Developments. *Comput. Ind.* **2006**, *57*, 490–503. [CrossRef]
5. Sasson, A.; Johnson, J.C. The 3D Printing Order: Variability, Supercenters and Supply Chain Reconfigurations. *Int. J. Phys. Distrib. Logist. Manag.* **2016**, *46*, 82–94. [CrossRef]

6. Kim, H.; Cha, M.; Kim, B.C.; Lee, I.; Mun, D. Maintenance Framework for Repairing Partially Damaged Parts Using 3D Printing. *Int. J. Precis. Eng. Manuf.* **2019**, *20*, 1451–1464. [CrossRef]
7. Holmström, J.; Gutowski, T. Additive Manufacturing in Operations and Supply Chain Management: No Sustainability Benefit or Virtuous Knock-On Opportunities? *J. Ind. Ecol.* **2017**, *21*, S21–S24. [CrossRef]
8. Chekurov, S.; Metsä-Kortelainen, S.; Salmi, M.; Roda, I.; Jussila, A. The Perceived Value of Additively Manufactured Digital Spare Parts in Industry: An Empirical Investigation. *Int. J. Prod. Econ.* **2018**, *205*, 87–97. [CrossRef]
9. Chekurov, S.; Salmi, M. Additive Manufacturing in Offsite Repair of Consumer Electronics. *Phys. Procedia* **2017**, *89*, 23–30. [CrossRef]
10. Attaran, M. The Rise of 3-D Printing: The Advantages of Additive Manufacturing over Traditional Manufacturing. *Bus. Horiz.* **2017**, *60*, 677–688. [CrossRef]
11. Kunovjanek, M.; Knofius, N.; Reiner, G. Additive Manufacturing and Supply Chains—A Systematic Review. *Prod. Plan. Control* **2020**, *33*, 1231–1251. [CrossRef]
12. Chaudhuri, A.; Gerlich, H.A.; Jayaram, J.; Ghadge, A.; Shack, J.; Brix, B.H.; Hoffbeck, L.H.; Ulriksen, N. Selecting Spare Parts Suitable for Additive Manufacturing: A Design Science Approach. *Prod. Plan. Control* **2020**, *32*, 670–687. [CrossRef]
13. Ngo, T.D.; Kashani, A.; Imbalzano, G.; Nguyen, K.T.Q.; Hui, D. Additive Manufacturing (3D Printing): A Review of Materials, Methods, Applications and Challenges. *Compos. Part B Eng.* **2018**, *143*, 172–196. [CrossRef]
14. Zijm, H.; Knofius, N.; van der Heijden, M. Additive Manufacturing and Its Impact on the Supply Chain. In *Operations, Logistics and Supply Chain Management*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 521–543.
15. Yang, S.; Tang, Y.; Zhao, Y.F. A New Part Consolidation Method to Embrace the Design Freedom of Additive Manufacturing. *J. Manuf. Process.* **2015**, *20*, 444–449. [CrossRef]
16. Sauerwein, M.; Bakker, C.; Balkenende, R. Annotated Portfolios as a Method to Analyse Interviews. *DRS2018 Catal.* **2018**, *3*, 25–28. [CrossRef]
17. Scott, K.A.; Weaver, S.T. To Repair or Not to Repair: What Is the Motivation? *J. Res. Consum.* **2014**, *26*, 43–44.
18. Sabbaghi, M.; Esmaeilian, B.; Cade, W.; Wiens, K.; Behdad, S. Business Outcomes of Product Repairability: A Survey-Based Study of Consumer Repair Experiences. *Resour. Conserv. Recycl.* **2016**, *109*, 114–122. [CrossRef]
19. Sauerwein, M.; Doubrovski, E.; Balkenende, R.; Bakker, C. Exploring the Potential of Additive Manufacturing for Product Design in a Circular Economy. *J. Clean. Prod.* **2019**, *226*, 1138–1149. [CrossRef]
20. Samenjo, K.; van Oudheusden, A.; Bolaños, J.; Flipsen, B.; Faludi, J. Opportunities For 3D-Printable Spare Parts: Estimations from Historical Data. In Proceedings of the 4th PLATE Virtual Conference, Limerick, Ireland, 26–28 May 2021.
21. Kietzmann, J.; Pitt, L.; Berthon, P. Disruptions, Decisions, and Destinations: Enter the Age of 3-D Printing and Additive Manufacturing. *Bus. Horiz.* **2015**, *58*, 209–215. [CrossRef]
22. Knofius, N.; Van Der Heijden, M.C.; Zijm, W.H.M. Selecting Parts for Additive Manufacturing in Service Logistics. *J. Manuf. Technol. Manag.* **2016**, *27*, 915–931. [CrossRef]
23. Frandsen, C.S.; Nielsen, M.M.; Chaudhuri, A.; Jayaram, J.; Govindan, K. In Search for Classification and Selection of Spare Parts Suitable for Additive Manufacturing: A Literature Review. *Int. J. Prod. Res.* **2020**, *58*, 970–996. [CrossRef]
24. Westerweel, B.; Basten, R.J.I.; van Houtum, G.J. Traditional or Additive Manufacturing? Assessing Component Design Options through Lifecycle Cost Analysis. *Eur. J. Oper. Res.* **2018**, *270*, 570–585. [CrossRef]
25. Yang, L.; Hsu, K.; Baughman, B.; Godfrey, D.; Francisco Medina, M.M.; Wiener, S. Design for Additive Manufacturing. In *Additive Manufacturing of Metals: The Technology, Materials, Design and Production*; Springer International Publishing AG: Cham, Switzerland, 2017; pp. 81–160. ISBN 978-3-319-55128-9.
26. Ganter, N.V.; Bode, B.; Gembarski, P.C.; Lachmayer, R. Method for Upgrading a Component within Refurbishment. *Proc. Des. Soc.* **2021**, *1*, 2057–2066. [CrossRef]
27. Wiberg, A.; Persson, J.; Ölvander, J. Design for Additive Manufacturing—A Review of Available Design Methods and Software. *Rapid Prototyp. J.* **2019**, *25*, 1080–1094. [CrossRef]
28. Leary, M. *Digital Design for AM*; Elsevier: Amsterdam, The Netherlands, 2020; ISBN 9780128167212.
29. Haruna, A.; Jiang, P. A Design for Additive Manufacturing Framework: Product Function Integration and Structure Simplification. *IFAC-PapersOnLine* **2020**, *53*, 77–82. [CrossRef]
30. Vaneker, T.; Bernard, A.; Moroni, G.; Gibson, I.; Zhang, Y. Design for Additive Manufacturing: Framework and Methodology. *CIRP Ann.* **2020**, *69*, 578–599. [CrossRef]
31. Lindemann, C.; Reiher, T.; Jahnke, U.; Koch, R. Towards a Sustainable and Economic Selection of Part Candidates for Additive Manufacturing. *Rapid Prototyp. J.* **2015**, *21*, 216–227. [CrossRef]
32. Park, M. Print to Repair: Opportunities and Constraints of 3D Printing Replacement Parts. In Proceedings of the PLATE: Product Lifetimes And The Environment, Nottingham, UK, 17–19 June 2015; pp. 270–276.
33. Terzioğlu, N.; Brass, C.; Lockton, D. 3D Printing for Repair: A Paradigm Shift in Fixing Our Relationships with Things. In Proceedings of the Sustainable Innovation 2016: Circular Economy Innovation & DesignAt: University for the Creative Arts, Epsom, UK, 7–8 November 2016; pp. 274–281.
34. Lorenzen, A.; Paape, A. *Leitfaden Für Den Einsatz 3D-Gedruckter Ersatzteile in Der Reparatur*; 2018. Available online: https://3d-reparieren.de/materialien-und-downloads/#broschuere (accessed on 28 September 2020).
35. Beerkens, T. Application of 3D Printing in Repair. Master's Thesis, Delft University of Technology, Delft, The Netherlands, 2017.

36. Agresti, A.; Coull, B.A. Approximate Is Better than "Exact" for Interval Estimation of Binomial Proportions. *Am. Stat.* **1998**, *52*, 119–126.
37. Roozenburg, N.F.M.; Eekels, J. *Product Design: Fundamentals and Methods*; Wiley: Hoboken, NJ, USA, 1995; ISBN 978-0471954651.
38. Terzioğlu, N.; Wever, R. Integrating Repair into Product Design Education: Insights on Repair, Design and Sustainability. *Sustainability* **2021**, *13*, 10067. [CrossRef]
39. Beerkens, T. Repair Using 3D Printing: 3 Reproduction. Available online: https://www.instructables.com/Repair-Using-3D-Printing-3-Reproduction/ (accessed on 6 December 2021).
40. Pozo Arcos, B.; Bakker, C.; Flipsen, B.; Balkenende, R. Practices of Fault Diagnosis in Household Appliances: Insights for Design. *J. Clean. Prod.* **2020**, *265*, 121812. [CrossRef]
41. Beerkens, T. Repair Using 3D Printing: 1 Decomposition. Available online: https://www.instructables.com/Repair-Using-3D-Printing-1-Decomposition/ (accessed on 3 November 2021).
42. Lipton, J.; Witzleben, J.; Green, V.; Ryan, C.; Lipson, H. Demonstrations of Additive Manufacturing for the Hospitality Industry. *3D Print. Addit. Manuf.* **2015**, *2*, 204–208. [CrossRef]
43. Brockotter, R. Key Design Considerations for 3D Printing. Available online: https://www.hubs.com/knowledge-base/key-design-considerations-3d-printing/ (accessed on 1 June 2022).
44. Bournias Varotsis, A. Understand and Fix Common STL File Errors. Available online: https://www.hubs.com/knowledge-base/fixing-most-common-stl-file-errors/ (accessed on 1 June 2022).
45. Simplify3D Print Quality Troubleshooting Guide. Available online: https://www.simplify3d.com/support/print-quality-troubleshooting/ (accessed on 1 June 2022).
46. Prusa Polymers Team Chemical Resistance of 3D Printing Materials. Available online: https://prusament.com/chemical-resistance-of-3d-printing-materials/ (accessed on 1 June 2022).