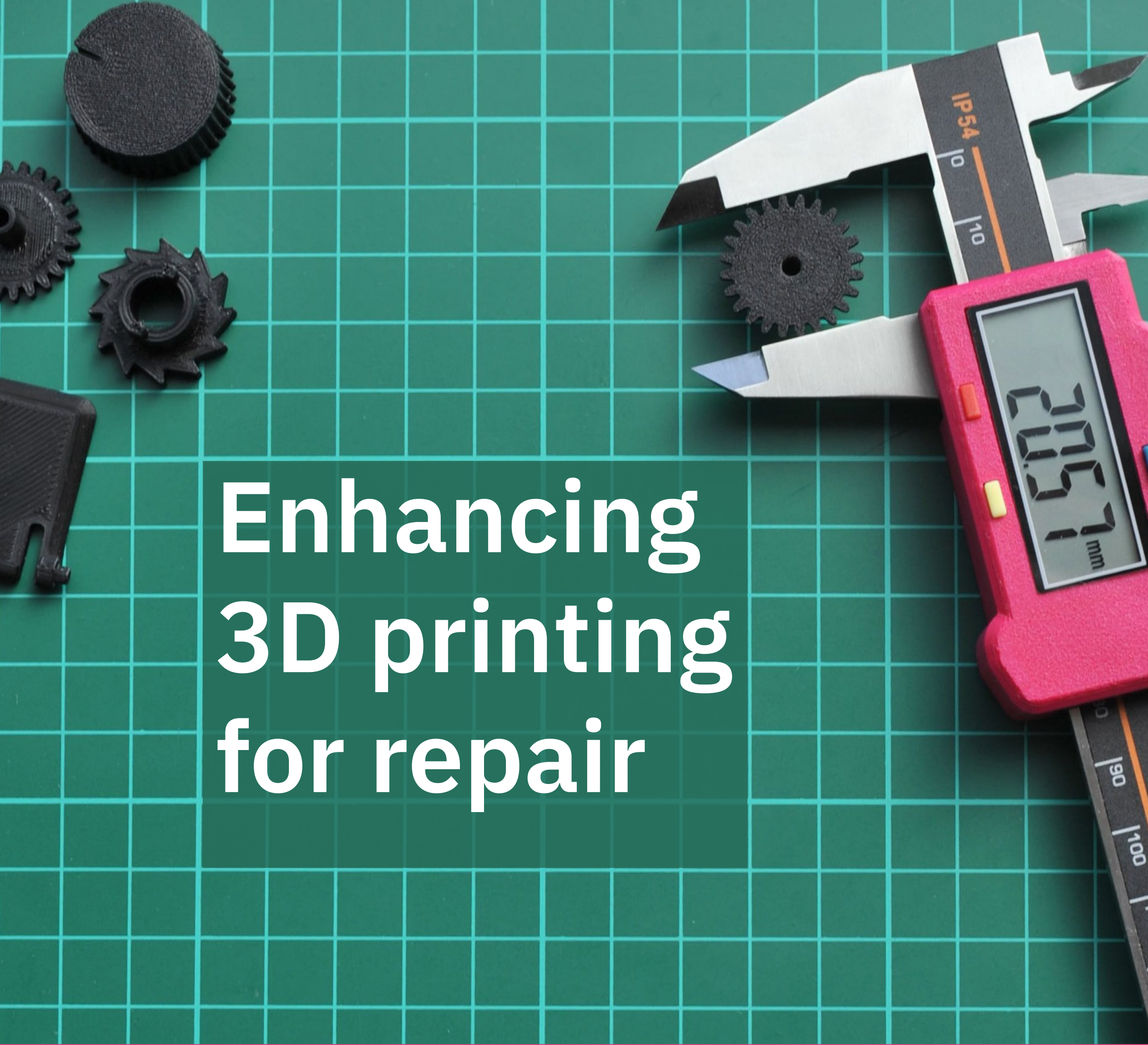

Enhancing 3D printing for repair

Designing a system that enhances the collaboration between repairers and makers

Tomas Vella Bamber
Master thesis
Integrated product design
Delft University of Technology
May 2020

TU Delft

Interreg North-West Europe SHAREPAIR

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Supervisory team
Chair: Dr. Ir. Flipsen, S.F.J.
Mentor: Dr. Mulder, I.J.

Preface

This thesis presents the results of my master graduation project within the Integrated Product Design master at the faculty of Industrial Design Engineering at Delft University of Technology.

My affinity with repair dates back to when I was in primary school. I was fascinated by people's ability to make, break and repair stuff and I wanted to learn how to make my ideas tangible and master the objects and tools that surround us. I soon found out that breaking stuff is very easy, but repairing and making new things is much more difficult. After breaking lots of stuff, I slowly learnt how to repair them and I started restoring things such as electrical appliances, bikes, mopeds and cars.

This project was a perfect match for my interests and skills, as well as for my personal vision: "Empowering individuals to master the technology that surrounds them." Through this project I want to encourage others to take up tools and repair their own products. However not everyone has the same skills and tinkering mentality, resulting in tons of waste which hurts our environment, local economies and personal freedom. That is why I want to use my design engineering skills to make repair more accessible and appealing to people.

I hope you enjoy reading my report!

Tomas Vella Bamber

Figure 1. A 3D printed part made for repairing a coffee machine

Executive summary

This project focuses on enhancing the accessibility of 3D printing for repairers by designing a system in which repairers can collaborate with makers.

Repair has become rare in societies with an abundance of cheap goods. However in recent years repair is making a gradual comeback in western culture. Citizen repair initiatives such as Repair Cafés have popped up in cities all over the world. They support people to fix their broken things.

The increasing popularity of the 'Maker Movement' and 3D printing has allowed skilled individuals to create, share and produce their own spare parts for repair. While most modern makers also repair things, most repairers are not capable of making things using digital fabrication methods like 3D printing.

To analyse why most repairers can't use 3D printing and how the 3D printing process can be changed, the context of repairers, makers, 3D printing and reverse engineering was explored.

The main findings were translated into design requirements that were used as guidelines in a conceptualisation process. During this phase multiple ideas were tested and iterated on in three different layers: information for repairers, physical tools for part measurement and communication with makers.

After a number of iterations a final concept was proposed that enables repairers to 'manually' 3D scan an object, using a caliper, and digitally share it with makers so that they can support them in replicating the object through CAD modelling and 3D printing.

The system was tested with a small group of repairers and discussed with experts. After implementing those insights, the final design is proposed.

The final design is a product service system that consists of a toolkit for repairers and an online platform through which repairers can collaborate with makers on 3D printing for repair projects. The toolkit contains a CyberCaliper, which is a special caliper that makes it easier for repairers to 'manually' 3D scan their desired part and post it on the platform. The platform is designed to become the place to be for requesting 3D printed spare parts online.

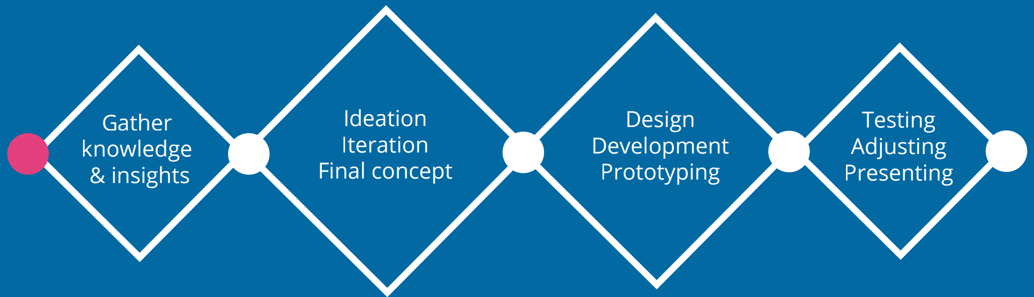
This graduation project is part of the ShaRepair project funded by the Interreg North-West Europe programme under grant agreement NWE982.

Contents

Terms and Abbreviations

3DP	Three dimensional printing
3DPR	Three Dimensional Printing for Repair
CAD	Computer Aided Design; method of designing 3D objects digitally.
Caliper	A multi-use measuring instrument that uses a sliding scale and can measure distances more accurately than a ruler.
FabLab	A space with tools and facilities where makers can go to build their projects and where they help each other.
FDM	Fused deposition modelling; a common 3D printing technique where a plastic filament is melted and extruded through a nozzle that builds up the desired shape.
Maker	Someone who makes things as a hobby using modern technologies.
PLA	Poly Lactic Acid, a common 3D printing plastic.
Repairer	Someone who repairs and maintains equipment for himself and others.
Repair Café	An organised gathering of volunteer repairers who fix broken appliances and objects of their fellow citizens for free. (Repair Café, n.d.)
SLA	Stereolithography is a form of 3D printing that uses resin and a UV light source to build the object suspended in the liquid resin.
Spare part	An interchangeable part that can be used to fix or replace broken units.

1. Introduction



This project explores the context of makers and repairers and how 3D printing can add value to repair. In this chapter the general goal and context for this project are presented as well as the general approach.

The utility of repairers is recognised by many people, yet they are undervalued in our society. The main goal of this project is to enhance the capabilities and the esteem of repairers by giving them access to 3D printing. This is done by designing a new workflow for 3D Printing spare parts for repair.

Repair has become rare in our consumer oriented society with an abundance of cheap goods. However in recent years repair is making a gradual comeback in western culture. Especially among environmentally aware people, tech enthusiasts and the maker community. Local repair initiatives such as Repair Cafés (Repair Café, n.d.) have popped up in many cities around the world. Governments and companies are starting to support these initiatives (ShaRepair, n.d.).
An interesting and promising trend of the last decade is 3D Printing, it has become a common instrument in the so called maker community. These hobbyist engineers are able to work with this digital fabrication method because they are familiar with engineering and computers. This allows them to create virtually any shape for their projects. If only repairers could use this tool to create spare parts that they badly need but that are no longer available to them, their capabilities and esteem would rise, hopefully inspiring new generations to get more involved in repair.
This project aims at using technology and design to enhance 3D Printing tools and workflows so that repairers can finally access this valuable new tool. The approach is aimed at enabling repairers and makers to work together on repair projects.

The context and scope of this project are focused around the maker community and the repair community. Both the repairer and maker communities come together regularly in local spaces such as FabLabs (FabLabs, n.d.) (Fabrication Labs for makers) and Repair Cafés (Gatherings where volunteers help repair people's products).

ShaRepair, an EU funded project

This project is part of the ShaRepair project funded by the Interreg North-West Europe programme under grant agreement NWE982. The goal of the ShaRepair project is "To decrease electronic waste from consumer products by scaling up citizen repair initiatives through the use of digital tools."
The end result of this project is meant to contribute to the goal by empowering citizen repair initiatives through the use of 3D printing.

Scope of this project

3D printing has become very popular among makers since the start of the RepRap project (Jones et al., 2011), an open source 3D printer project that was started in the mid 2000s. Another factor was the expiration of several important 3D printing patents in 2009 (Crump & Muir, 1992). Most people can afford a 3D printer nowadays, a cheap but popular Chinese printer can be bought for 200 euros (Tweakers, n.d.), and the internet allows for easy 3D file sharing on online platforms such as Thingiverse (Thingiverse.com, n.d.) and GrabCAD (GrabCAD - Library, n.d.). 3D printing promises great convenience for people, enabling them to download and print physical products and spare parts at home.
However 3D printing is still not catching on very much in the repair community, one of the reasons for this is that 3D printing is a complex, multidisciplinary process. This project is focussed on improving this workflow so that it can be accessed by people who don't possess all the skills that are currently necessary.
The 3D printing process requires a range of specific engineering and digital skills. In figure 1, a typical 3D printing process is visualised, including the activities and skills that are involved.

The scope of the project includes the whole workflow, but the main focus is placed on the first and the last step. The modelling, slicing and printing are not focussed on in the design proposal in order to leave room for variability. The middle three steps highly depend on personal preferences, equipment and software that evolves rapidly.

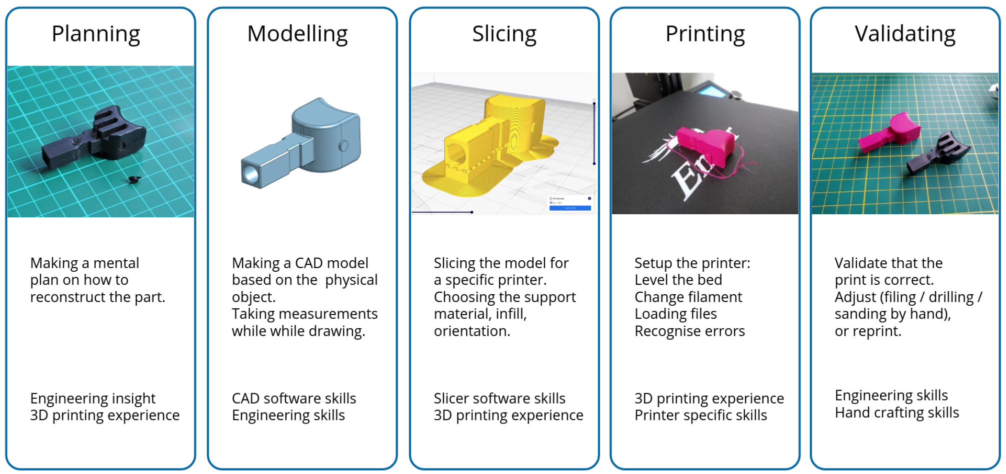


Figure 2. A typical 3D printing for repair workflow

Project approach

The design process is visualised and the objectives are divided into sub tasks.

The design process of this project consists of five phases, which are visualised in figure2. Each phase consists of a diamond which represents diverging and converging. Based on the double diamond method (Banathy, 1996). The first phase is focused on finding the right problem. The second and third phase are focused on designing and developing a concept. The fourth phase is validating the final concept and presenting the final design.

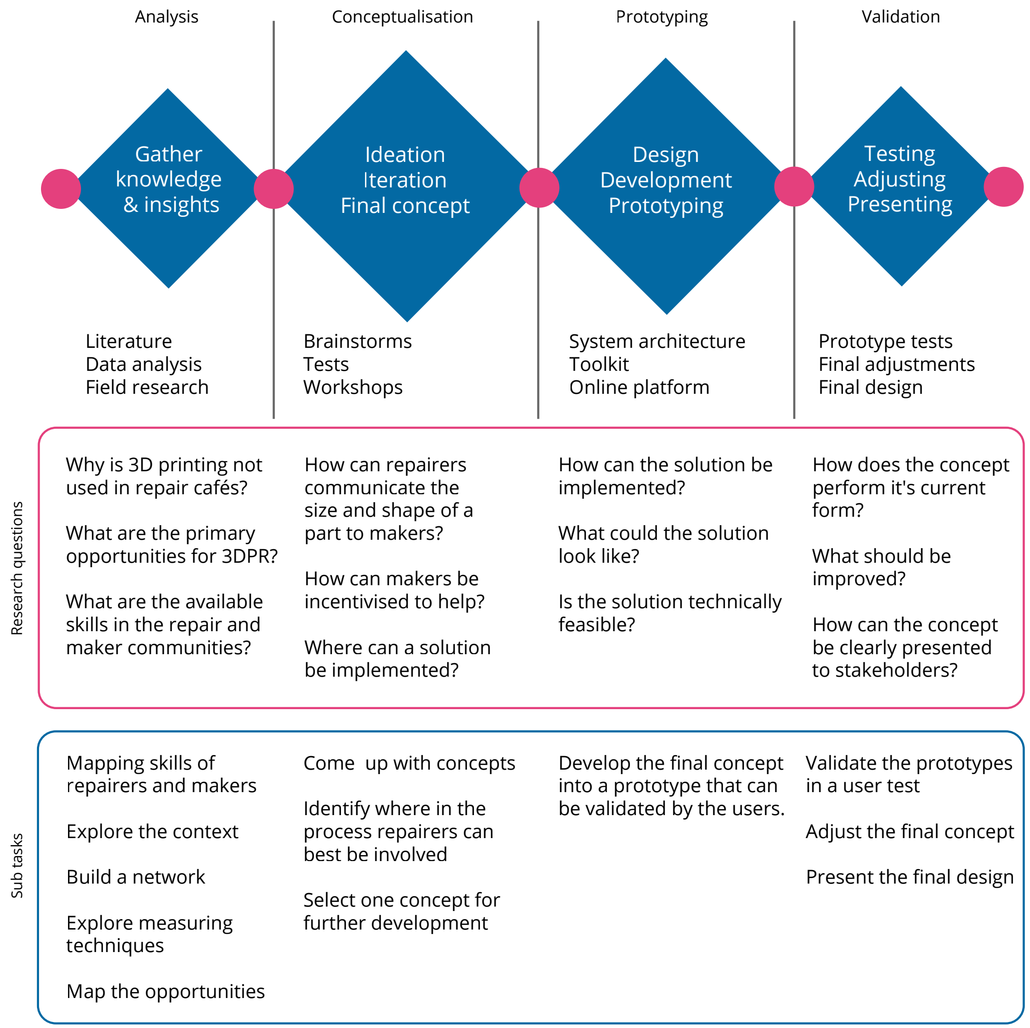
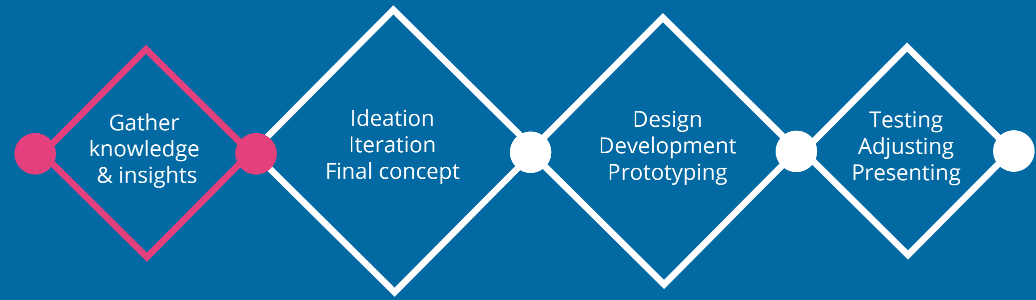


Figure 3. The design process

2. Analysis



In this chapter the context of this project is explored through literature and data analysis as well as some field research. The results are split up into the following sections: the context of the repair and maker communities, the workflow and requirements of 3D printing spare parts and 3D scanning and measuring techniques.

Main research questions for this chapter

As a basis for the analysis phase the following research questions were formulated as guidance.

- Why is 3D printing rarely used in repair communities?
- What are primary opportunities for 3D printing for repair?
- What are the available and relevant skills in the repair and maker communities?

Research methods

The following three methods were used during the analysis phase.

Literature research

Literary sources were found about the history of the maker community, the rise of 3D printing, and the repair community.
Technologies and products for 3D scanning and 3D printing were explored and compared by going through literature, web-shops and reviews to find specifications. Old measurement and 3D description technologies and drafting techniques were explored.

Data analysis

In order to gain insight into the potential for 3D printing within the repair context, databases such as the Repair monitor(RepairMonitor.Org, n.d.), the Restarter project("Restart Project," n.d.) and Thingiverse(Thingiverse.com, n.d.) were analysed for relevant data and statistics.

Field research

Visiting repair and maker communities to observe and interview them in order to get an overview of the available skills, personal motivations, limitations and other potential insights for this project.

Deconstructing the context

The context of this project covers two different communities of people. The repairer in this case is centered around the Repair Café (Repair Café, n.d.) and the maker is centered around the FabLab (FabLabs, n.d.). In reality this is not the case for every maker or repairer, however these places can give good insights in the type of people that visit them. Therefore these places were the focus of the research.

Exploring the repair community

Repair has been a part of human activity ever since we started building things. Our bodies as well as the materials around us are subject to entropy. Things degrade and break down over time due to wear, accidents and exposure to the natural environment. In order to keep things working they need to be maintained and repaired regularly.
Repair has become less common in industrial societies where products are cheap and labour is expensive. However in recent years it is making a comeback. Environmental awareness and the idea of the Circular Economy together with economic recessions and the free sharing of information on the internet have contributed to this.
iFixit (iFixit, n.d.) is a platform for repair manuals and tools are committed to helping consumers repair their own products and protecting people's right to repair by lobbying for right to repair legislation in the US and EU (The Repair Association, n.d.).
Repair Café is an example of how repair communities can form locally. It is an initiative that was founded in the Netherlands in 2009 by Martine Postma. The idea is that local repairers and consumers with a broken product gather in a café and try to fix the products. For the repairers it is a social gathering in which they apply their repair skills and are challenged to learn something. For the consumers it's an opportunity to get a precious product working again in return for a small voluntary donation.

Repair Café Delft

In the first visit to the local Repair Café in Delft, the processes were observed. The repairs were closely observed in order to identify situations in which 3D printing could add value. The expectations from the repairers were insightful. Some suggested printing discontinued parts such as a rare LEGO piece. Some of the expectations were too pessimistic. A repairer said: "I think it takes too much time to print anything, I heard it takes 12 hours to print something." Others were too optimistic: "This cracked toaster part can be printed right?" During the session only about three fixes were identified where 3D printing could add value, of a total of around 70 repairs. In appendix B more info about these observations can be found.

The maker community

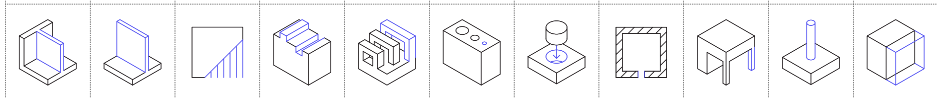
Since the emergence of the internet, people have been sharing their inventions and designs. Make magazine, has built itself around an audience of “makers” which started to gather locally in so called Makerspaces, Hackerspaces or FabLabs (FabLabs.Io, n.d.). These spaces became hubs for DIY making, prototyping and educative purposes. Used by hobbyists, schools and startups to fabricate things. Usually these spaces have equipment such as 3D printers, laser cutters and power tools that enable their visitors to digitally and manually fabricate projects.
Companies such as Adafruit (Inside Adafruit, 2017), Arduino (Kushner, David, 2011) and Raspberry Pi (“Raspberry Pi Foundation,” n.d.) have thrived by providing makers with tools. An open source 3D printer company named Prusa (“Prusa Research,” n.d.) has been at the center of 3D printing targeted at makers. Their designs are open source which means that everyone can use them and contribute to them. The ethos of sharing information, code and design files has become the basis for the maker community, it empowers individuals to harness the power of the community by copying, remixing and sharing.

Local maker communities

HCC 3D in Delft (HCC!3d, n.d.) is a group of 3D printing enthusiasts that share their experiences and learn new things during their monthly meet-ups. At the meeting I attended they were evaluating their “homework” for an Onshape CAD (Onshape, n.d.) course from the previous session. The goal of the observations was to find out what the skill level of the members were. The skill level varied among the 12 members. Out of 12, only 3 members managed to finish the assignment, which was moderately challenging. So my conclusion was that only around a quarter of the members were skilled enough in CAD for doing 3D printing for repair. In appendix C the visit is reported in detail.
A visit was made to FabLab KU Leuven (Fablab Leuven, n.d.), this FabLab is open to the public and situated inside the Mechanical Engineering faculty of the university. Therefore it is mostly used by students. The founder of the FabLab was interviewed, he was quite skeptical about using 3D printing for repair. His main concern was that people were much too optimistic about the possibilities of 3D printing, causing them to get many requests that were infeasible, costing them time and achieving nothing. In appendix D this visit is reported in detail.

The 3D printing ecosystem

In the past two decades, 3D printing has become much more accessible to businesses and individuals. The internet made the development of 3D printing in online communities possible. Companies like Prusa and Ultimaker were able to produce their own line of 3D printers based on open source technology and the FDM (fused deposition modelling) patent (Crump & Muir, 1992) that expired in 2009.
Next to the FDM, consumer level printers, high end technologies were developed such as SLS, SLA and metal printing(3D Hubs, n.d.), aimed at industrial applications. These are not available to consumers yet but may become so eventually. SLA (stereolithography) printing has become cheaper and more accessible in recent years. In appendix E more info can be found about 3D printing technologies and workflows.
On top of the 3D printers themselves another layer of companies came into being, the software and service providers, these include: CAD software, Slicing software and online 3D marketplaces such as Thingiverse.
Another service model is the online printing as a service hub or marketplace. 3D hubs was founded in 2009, it grew out to become a platform on which makers with printers could take paid print jobs and ship them locally. At their peak they featured thousands of printers around the world. Remarkably in 2018 the management decided to drop the peer to peer hubs and focus on it’s centralised hubs for financial reasons (3Dprint.Com, 2018).
Today, 3D hubs and Shapeways (Shapeways, n.d.) offer online 3D printing as a service, which allows people to access high quality 3D printers.
FDM printers have become much cheaper in recent years. Chinese manufacturers are building printers of reasonable quality for the masses. Models such as the Creality Ender 3 are available for under 200 Euro (Tweakers, n.d.), and almost match the printing quality of much more expensive printers like Prusa and Ultimaker (Ultimaker, n.d.).



	Supported walls	Unsupported walls	Support & overhangs	Embossed & engraved details	Horizontal bridges	Holes	Connecting /moving parts	Escape holes	Minimum features	Pin diameter	Tolerance
	Walls that are connected to the rest of the print on at least two sides.	Unsupported walls are connected to the rest of the print on less than two sides.	The maximum angle a wall can be printed at without requiring support.	Features on the model that are raised or recessed below the model surface.	The span a technology can print without the need for support.	The minimum diameter a technology can successfully print a hole.	The recommended clearance between two moving or connecting parts.	The minimum diameter of escape holes to allow for the removal of build material.	The recommended minimum size of a feature to ensure it will not fail to print.	The minimum diameter a pin can be printed at.	The expected tolerance (dimensional accuracy) of a specific technology.
Fused deposition modeling	0.8 mm	0.8 mm	45°	0.6 mm wide & 2 mm high	10 mm	Ø2 mm	0.5 mm		2 mm	3 mm	±0.5% (lower limit ±0.5 mm)
Stereo-lithography	0.5 mm	1 mm	support always required	0.4 mm wide & high		Ø0.5 mm	0.5 mm	4 mm	0.2 mm	0.5 mm	±0.5% (lower limit ±0.15 mm)
Selective laser sintering	0.7 mm			1 mm wide & high		Ø1.5 mm	0.3 mm for moving parts & 0.1 mm for connections	5 mm	0.8 mm	0.8 mm	±0.3% (lower limit ±0.3 mm)
Material jetting	1 mm	1 mm	support always required	0.5 mm wide & high		Ø0.5 mm	0.2 mm		0.5 mm	0.5 mm	±0.1 mm
Binder jetting	2 mm	3 mm		0.5 mm wide & high		Ø1.5 mm		5 mm	2 mm	2 mm	±0.2 mm for metal & ±0.3 mm for sand
Direct metal Laser sintering	0.4 mm	0.5 mm	support always required	0.1 mm wide & high	2 mm	Ø1.5 mm		5 mm	0.6 mm	1 mm	±0.1 mm

Figure 4. Guide for selecting suitable 3D printing technology, courtesy of 3D Hubs

Making it fit

One of the foremost requirement for a spare part is that it fits into place. In order for something to fit, it needs to be the correct size. Designing and making something of the correct size requires adequate measurement methods. Here we look at the science of measurements and the available methods that are relevant for this project.

The importance of accuracy

The success of 3D printed part sharing depends largely on maintaining a certain accuracy. One milimetre must be the same for the repairer, the designer and the 3D printer. Desktop FDM printers can have an offset of 0.5mm.(Dimensional Accuracy of 3D Printed Parts, n.d.) Nevertheless it is important to keep the measurements close to the real size of the broken part. The printer offset can be minimised by using accurate measuring tools. Measuring the broken object and validating the finished print by measuring it and comparing it to the original measurements. Allowing the maker to adjust for the offset if necessary. Therefore if both the maker and the repairer use accurate enough tools, the average tolerance of small plastic injection moulded parts can be achieved ±0.1mm(StarRapid, n.d.).

Classic measuring tools

Metrology, the science of measurement, dates back to the beginning of human technology. The introduction of the metric system by France and mainland Europe in the early 1800's made measurements much more consistent, allowing people over vast distances to communicate precise measurements and collaborate in engineering projects. (Moore, 1970) Fast forward 200 years, and we are in the midst of a digital revolution. The measuring tools have been digitised but their classical forms have stayed with us. The Caliper that was invented hundreds of years ago, has been digitised in the 80s. (Mitutoyo, n.d.) More about the history of metrology can be found in Appendix G. The digital caliper is now produced by many Chinese firms for a very cheap price. The cheapest plastic calipers can be bought from 5 euros, with an accuracy of ±0.2mm. Mid-range calipers cost 25 euros promising an accuracy of ±0.02mm. High-end Japanese calipers are usually 100 euros or more, also promising an accuracy of ±0.02mm. Compared to analogue or Vernier calipers, digital calipers have the advantage of having better readability for people with bad eyesight, and the measurements don't have to be translated to using the Vernier scale.

Figure 5. A mid-range digital caliper

The promise of 3D scanning

Along with 3D printing, 3D scanning techniques have evolved rapidly in recent years. Open source scanners such as the FabScanPi are available for cheap, however their scan quality is sub optimal. Tests with the FabScanPi can be found in Appendix I. Professional scanners yield better results and accuracy, but that comes at a cost. Accuracy below 0.1mm easily costs 2500 or more, the Einscan-SP (All3DP, 2017) is an example. This is not the only problem with 3D scanning however. Reverse engineering through 3D scanning takes lots of skill and effort. Reflective surfaces must be covered with spray foam or paint. Scanning can take a long time. And then the reverse engineer must repair and rebuild the 3D mesh, which is always imperfect, into a 3D model that is ready for printing. Which often means starting from scratch and using the scan as a guide.

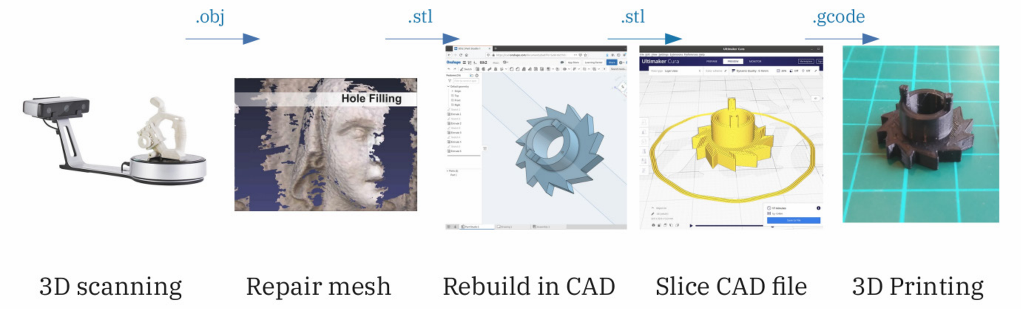


Figure 6. A typical 3D scanning workflow

3D scanning and ruler apps

Various apps are available such as Qlone (Qlone, n.d.), and Ruler app(Ruler App, n.d.). They rely on the phone camera for taking the measurements. However this poses some problems. Phone cameras vary for each phone. They are subject to many variables such as image deformation. This makes it very difficult to get accurate measurements from them. Using a photo ruler app, the deformation, parallax can cause up to 1mm offset. 3D scanning apps use a process called photogrammetry to build a 3D model. This can cause the 3D models to warp slightly of their real shape. In order to get accuracy out of them all the conditions must be ideal, this also requires expensive gear and lots of experience. Tests with photogrammetry in Meshroom(AliceVision, n.d.) and a photo ruler app can be found in Appendix I.

Comparing measuring tools

Because measuring is the basis of creating a part that fits, the following accessible measuring technologies were compared in terms of cost and accuracy, see figure 7.

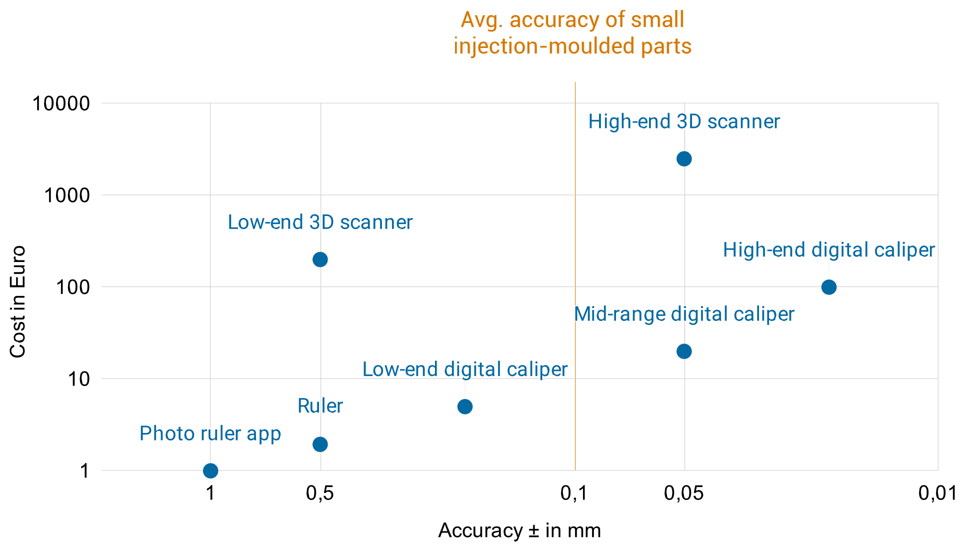


Figure 7. Accuracy versus cost of measuring tools

In order to develop a concept that uses the most suitable technology, the measuring techniques were also scored in terms of cost, accuracy, learning curve and speed of measurement. The results can be seen in figure 8.
Learning curve is relevant when it comes to teaching new users to use the workflow. Speed of measurement is relevant when limiting the time needed from the users.
Comparing the scores we can conclude that the digital caliper comes out as the absolute winner, scoring high in all categories. Surprisingly, the high-end 3D scanner comes in fourth place, beaten by the ruler and the phone app. A more detailed comparison can be found in Appendix G.

	Cost	Accuracy	Learning curve	Speed	Total score
Mid-range digital caliper	4	5	4	5	**18**
High-End 3D scanner	1	4	2	2	**9**
Phone ruler app	5	1	3	3	**12**
Low-End 3D scanner	3	2	1	1	**7**
Ruler	5	1	5	4	**15**

Figure 8. Ranking measuring methods for 3D printing for repair

Describing a 3D object

In order to help people create an object or spare parts, they need to be able to describe and communicate these objects. Therefore we need to explore how objects in the real world can be described on an analog or digital medium.
Before the digital revolution, engineers designed their objects on the drafting table. Using pen and paper to create 2D projections of a part was tedious work that demanded focus and discipline. The copy or blueprint of these drawings were the instructions for machinists to machine the part. See Appendix H for more info on engineering drawing.

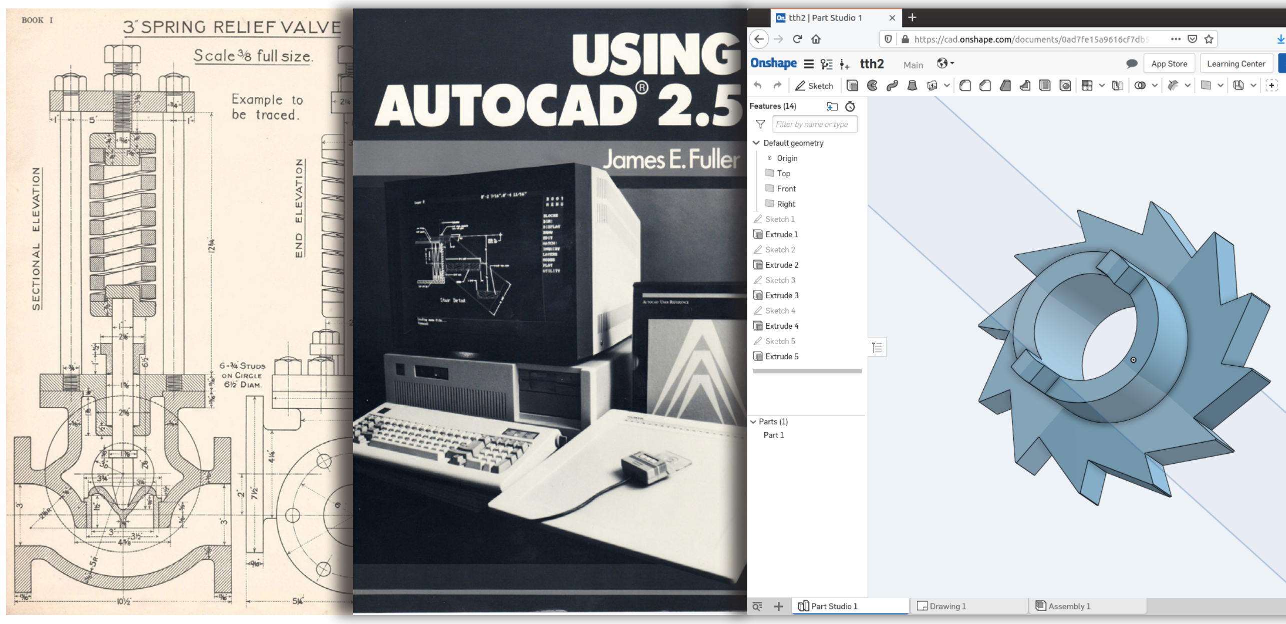


Figure 9. The evolution of engineering drawing to CAD modelling

Nowadays most people can afford a computer that is able to run CAD programs. The software itself has become extremely versatile and sometimes user friendly (for engineers). Browser based apps like Onshape (Onshape, n.d.) even allow CAD to be run on almost any platform. Free, open-source variants like FreeCAD (FreeCAD, n.d.) and openSCAD (OpenSCAD, n.d.)make CAD accessible to almost everyone, although they have a steep learning curve. Another problem with CAD software is that it evolves rapidly and can become incompatible and inaccessible over time. In order to make a long lasting system it should not depend entirely on one type of CAD software, especially proprietary ones. For a more detailed comparison of CAD software, see Appendix H.

3D printing & repair databases

Repair databases

Organisations such as Repair Café, Restarter and iFixit have pledged to conform to share their data according to the Open Repair Standard (“Open Repair Alliance,” n.d.). This is a standard in which the product category, brand, model, year of manufacture, repair status and problem description. These databases with around 30,000 entries were searched for potential repairs that could benefit from 3D printed parts, to find out how often spare parts are needed and to what extent 3D printing is already being used.

Are spare parts needed?

From the Restart project dataset (“Restart Project,” n.d.), the instances in which spare parts were needed were identified and compared to those in which they were not needed.
After filtering of the data approximately 22.5% of repairs were recorded that needed spare parts, and 77.5% that didn’t require it. Entries with no data about spare parts were discarded from this analysis. Details of this analysis can be found in appendix I.

Current application of 3D printing in repair

There were only seven recorded instances where 3D printing was already applied in the repair databases. From this we can conclude that 3D printing is currently not applied significantly in repair initiatives. For more details see appendix I.

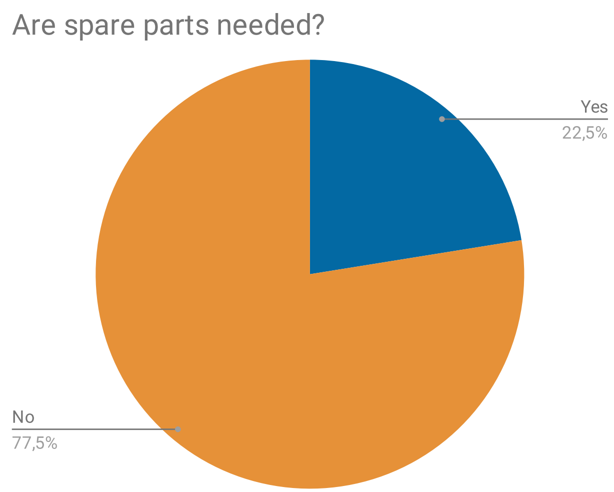


Figure 10. The need for spare parts for repairs (Restart Project, n.d.)

3D model databases

Thingiverse (Thingiverse.com, n.d.) and MyMiniFactory (MyMiniFactory, n.d.) are online platforms where people share 3D printable files. The platforms were searched for files that are related to repair in order to see how many spare parts are already available, and which parts are popular. For more info see appendix I. From the gathered data we can conclude that 3D printing for repair is being applied by makers, however in limited numbers. There are dedicated pages on which spare parts are being shared. The search results are polluted by non-repair parts, including upgrades, tools and objects that are related to the appliances. Another finding was that MyMiniFactory features a free part request option on their site, it links to a Google forms asks some info and “pictures next to a coin/ruler”, this raises the question what the success rate of those requests is.

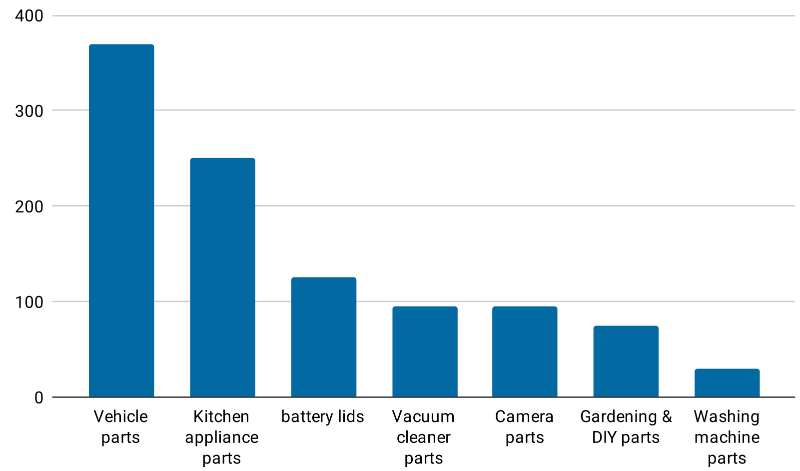


Figure 11. MyMiniFactory repair categories

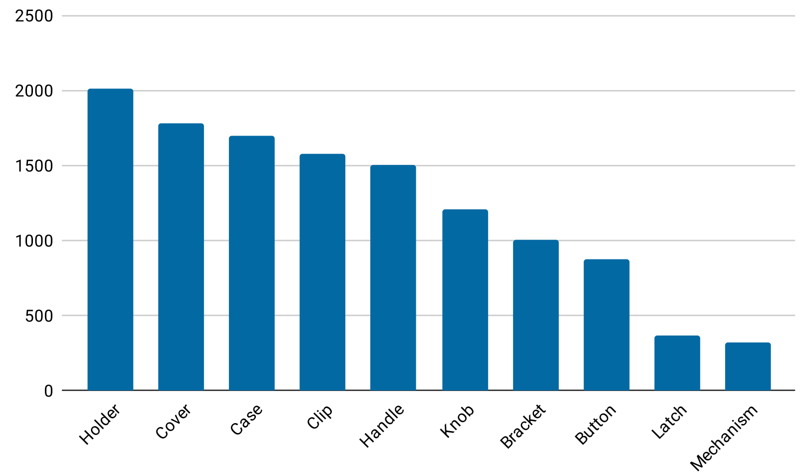


Figure 12. Thingiverse repair related search terms

Conclusion

To summarise the insights from the analysis, answers are provided to the relevant research questions.

Answering the main research questions

Why is 3D printing rarely used in repair communities?
The repair databases show that almost no repairs have been done using 3D printing. This is because it is a complicated multidisciplinary process and most repairers only master part of the skills that are necessary. Next to the skills there seems to be a lack of knowledge about 3D printing and its benefits in repair. Repairers are very enthusiastic about 3D printing but they underestimate its complexity, therefore their expectations need to be managed.

What are primary opportunities for 3D printing in repair?
The low hanging fruit for 3D printing can be found in simple, plastic, precision parts such as: Knobs, handles, flanges, rings, holding mechanisms and clamps. These are parts that are currently being 3D printed by makers.

What are the available and relevant skills in the repair and maker communities?
Repairers tend to be good in the mechanics and electronics. Lots of skill and experience with disassembly, soldering, glueing, maintaining and reassembly.
Makers tend to be good at design, engineering and digital fabrication they invent and make their own things.
The skills of makers and repairers varies wildly, some are very multidisciplinary, some are highly specialized, some are novices, some are experts.

Additional questions that were answered

How can repairers communicate their part requirements effectively to makers?
Avoiding complex computer skills, utilising their mechanical strengths.
Using measuring tools such as calipers that are easy to use, fast and accurate enough.
Describing the object effortlessly for example by taking a set of photos of the object.

How can makers be incentivised to help repairers 3D print parts?
They love helping others, but their time is in short supply, therefore their time should not be wasted. Their time is worth quite a lot of money, but their enthusiasm and willingness to help could trigger them if they feel like they can make a difference.

How can the solution be implemented effectively?
The Repair Café in Delft is a good pilot location because it is one of the busiest Repair Cafés in the world. Also, most of their volunteers are highly skilled and fast learning, retired engineers.

Which measuring technique is most suitable for repairers?
The digital caliper is currently the cheapest, most accurate and easy to use measuring tool for reverse engineering. Based on the ±0.1mm accuracy requirement defined in the analysis, all the measurement techniques are deemed unsuitable for 3D printing for repair except for high-end 3D scanning and digital calipers. This choice is easily made when comparing the price, time intensive and highly complex process of 3D scanning, to the simplicity, ease of use and familiarity of the digital caliper.

Could 3D printing add significant value to citizen repair initiatives?
Data from the repair database and 3D model platforms shows that a considerable amount of repairs could benefit from 3D printing. Another analysis showed that in 3D printing databases a significant amount of spare parts can be found. During the first visits there was only a small demand for 3D printed parts at the Repair Café, but this will likely increase when the tool is adopted into their workflow. See iteration 4 for the final Repair Café visit.

Additional insights

Repairers are very enthusiastic about 3D printing and underestimate its complexity.
The repairers expressed lots of enthusiasm about the project. During the test at the Repair Café however lots of false assumptions were held which resulted in many unfeasible print requests. Only two feasible requests were made during the first “maker-prototype” session. However other specialised repairs such as clock maker seem to attract more than enough clients. Time will tell if word of mouth can attract more 3D Printing compatible repair jobs.

Some repairers are tech savvy and already own a 3D printer.
At RC Delft there were two repairers who already owned a 3D printer, one was moderately experienced in CAD, the other was a novice. Although they own a printer they don’t yet have the skills to fully deploy it as a repair tool.

CAD software used by makers varies and evolves rapidly over time.
Each maker seems to have their own favourite software package. Some packages are free for a limited time period before they are put behind a paywall.
Makers with CAD skills are in short supply and most live in cities that have an engineering industry or university.
The online sharing of 3D files enables communities of people to work together all over the world. The success of Thingiverse, 3D Hubs and Prusa show that the maker community has considerable size, enthusiasm and willingness to share.

Requirements

Based on the analysis phase, a list of requirements was made that can be used to validate new concepts. The requirements focus on the needs of a repairer engaging in 3DPR.

Accuracy
The system should allow for a level of accuracy that is suited to the scenario in which it is being used. For small injection moulded plastic parts a tolerance of ±0.1mm is typically allowed(StarRapid, n.d.). In order to match the tolerances of original parts this has been set as a requirement.

Costs
The costs for the users should be minimised. DIY repairers and makers often have a tight budget and comparable repair tools usually cost less than 70 Euros. (Toolkits, n.d.) By making use of existing infrastructure and hardware, the costs can be kept low.

Speed
In order to make the effort worth it for smaller repairs, and in order to incentivise makers to help, the process should not be too time intensive. Therefore the workload for taking, sharing and interpreting measurements should be as low as possible. Also the workload should be fairly balanced between maker and repairer to keep them both equally committed.

Learning curve
In order to make the workflow accessible to a broad range of repairers, the learning curve should not be steep. An average repairer should be able to learn the workflow in a one hour workshop. This can be accomplished by using techniques and workflows that are familiar to people, as well as focussing on the usability of the design.

Reliability
The communication methods should be reliable, not subject to systemic errors which undermine the success of the repairs. These could be measurement errors, miscommunication or wrong expectations from repairers or makers.

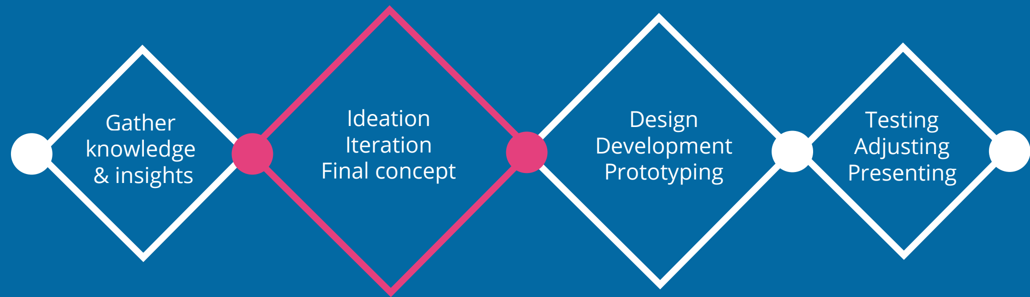
Versatility
The system should allow for diverse use cases and user backgrounds. General parts and objects (of a certain size that can be 3D printed in common FDM printers (Design Considerations - 3D Hubs, n.d.)) should be reproducible by using the system. It should not obstruct advanced or creative users' capabilities with unnecessary rules or limitations.

Scalablility
The concept should be scalable so that it can have a positive impact on a large group of people. The digital aspects of 3D printing already strengthens this.

Discussion

Several conditions may have skewed the results in one way or another. Below the most important doubts are discussed that may require further research in the future to get a more definitive answer:
The observations were mainly done at the Repair Café at Science Center Delft, which is one of the biggest in the world by amount of repairs. Observations on this location may not be representative for other Repair Cafés. Also, Delft is a region with many engineers, working and pensioned, this probably causes the skill level of the repairers to be higher than average for Repair Cafés. This makes it easier and more forgiving to test in the beginning, but eventually the concept must work for the average Repair Café volunteer.
The data from Thingiverse was not checked for feedback from makers, for some percentage of cases the spare parts may not have been adequate or reliable for the repair. This may have produced overly optimistic results.
Future developments in 3D scanning and AI may eventually make the process of reverse engineering completely automated, replacing the need for measuring and CAD drawing in many cases. In terms of computer vision the reverse engineering process can be compared to driving a vehicle, which can be done fully autonomous. In order to be future proof, this development needs to be taken into account.

3. Conceptualisation



In this chapter, the main project vision is formulated from which three concept layers are derived. These layers were used to as a basis for the ideation, conceptualisation and iteration phases that are presented in this chapter as well.

Project Vision

A significant amount of products break and are not repaired because the spare parts are not available. 3D Printing has the potential to give repairers new capabilities and the power to create new parts that are not available. This capability is currently not accessible to most repairers because the process is too complex and unintuitive. By dividing the current 3D printing workflow into smaller steps, by assisting repairers in the identification of objects that can be 3D printed and by assisting them in communicating their wishes to makers. The skills gap can be bridged between repairers and makers using digital media. This will allow repairers to initiate the process by themselves and communicate a spare part description to makers who can take over the process from there.

Main concept layers

From the research conclusions (see chapter 2) and the project vision, the following layers were defined to guide the conceptualisation and embodiment process.

Information layer: Guide & Teach repairers

Repairers have skills and knowledge that don't overlap with the 3D printing process. Because 3D printing is quite an unintuitive way of making something, it takes time to get used to its limitations and possibilities. Therefore it is important to guide repairers in the beginning to identify what is possible and what isn't. Also it is important to teach them some basic theory about the process, so they can orient themselves throughout the process.
For example: A digital guide that helps repairers identify parts that are suited for printing and filters requests that are not suitable.

Physical layer: Measure and describe needs to makers

In order for repairers to collaborate with makers, there needs to be clear and unambiguous communication. Repairers can currently communicate by physically giving or sending a broken part to a maker in order to reproduce it. However this limits the speed and efficiency of the communication. By digitising this communication a large pool of makers and repairers can collaborate in a much more efficient way.
For example: A tool that enables repairers to record the dimensions and geometry of a spare part and send them to a maker anywhere on earth.

Communication layer: Communication & implementation

In order for this project to make a significant contribution to the repair community, there needs to be actual implementation of the final concept. A local implementation at Repair Café Delft could be made, where physically makers attend the Repair Café and help repairers. However, this type of local implementation is not easily scaleable. In order to make a more sizeable impact and help repairers all over the world, the project should be made digital, so that it can spread more quickly online.
For example: A strategy to implement an online platform and kick-start a 3D printing for repair movement online. Starting at local Repair Cafés to validate the concepts before going public and expanding online.

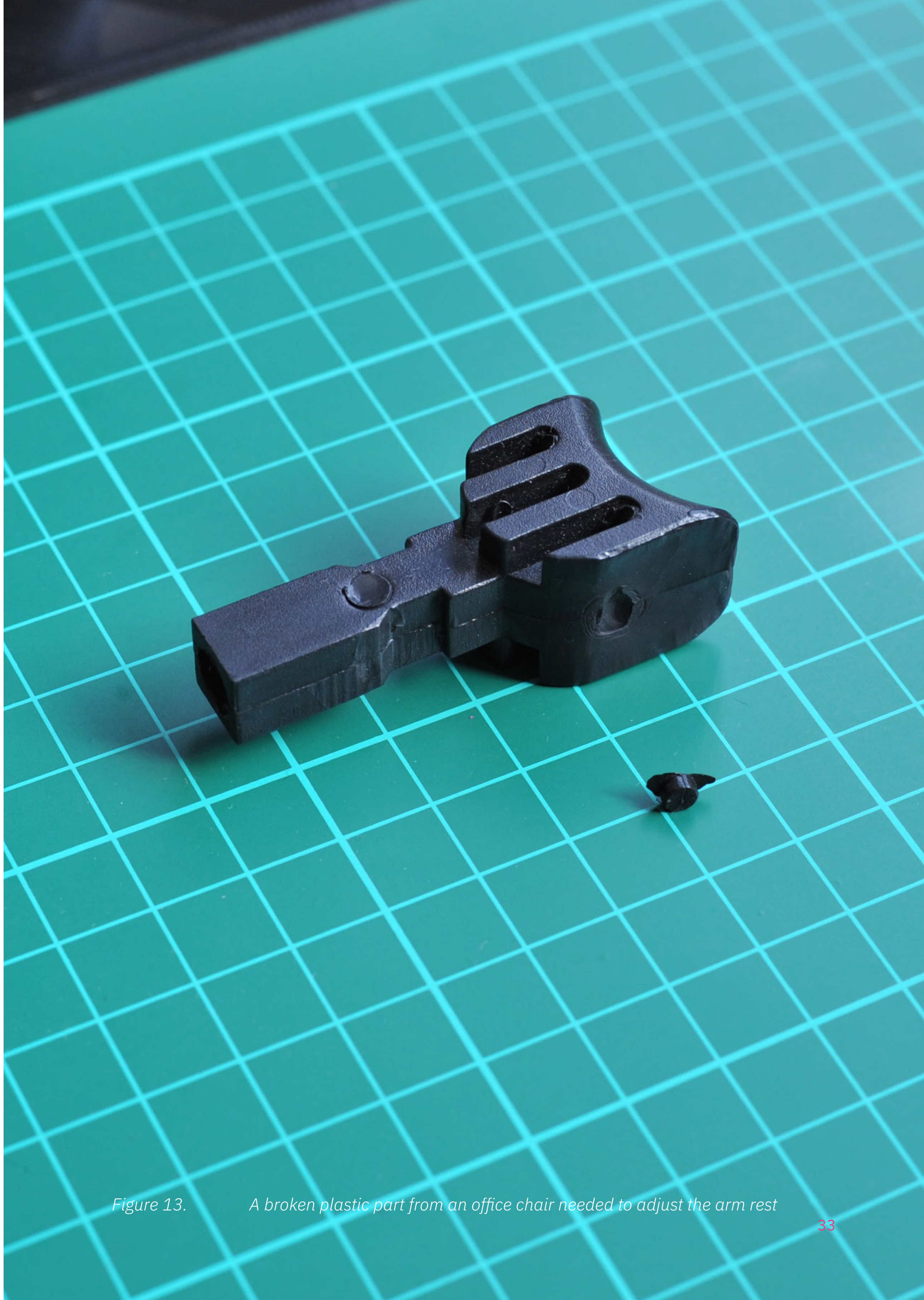


Figure 13. A broken plastic part from an office chair needed to adjust the arm rest

Ideation

Through brainstorming the main concept layers were translated into ideas that fit within this three layer system. The Information layer, which includes educational methods for the repairers. The physical layer, which means alternative 3D scanning tools and methods. And the Communication layer which includes methods of communicating between repairers and makers. More ideation sketches can be found in appendix J.

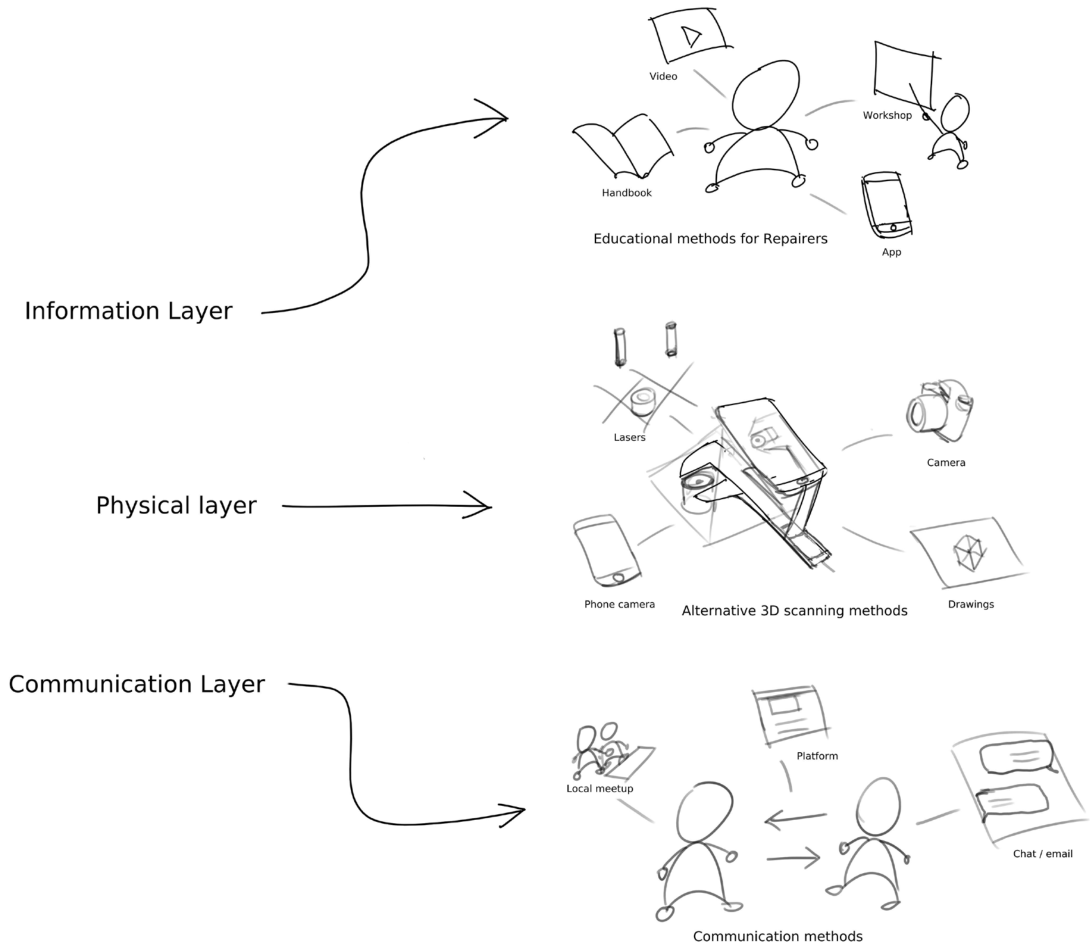


Figure 14. Visualisation of the ideation process

Iterations

For the final concept direction, a mix up was made between the three idea directions, combining their strongest points see figure 15.
The final concept is a system which combines a new method of manual 3d scanning with a digital communication system. It allows repairers to manually scan their broken part, and send it to a maker. The details of the system will be defined through iterations explained in the next pages.

Figure 15. Visualisation of the iteration process

First iteration

The first iteration was based on ideas that emerged from the ideation phase. The concepts per layer and main insights are described below. A more detailed report on the first iteration can be found in appendix K.

Information layer: educational app

Guiding repairers through the process is one way to get them more involved. Filtering infeasible print requests is important to manage expectations of the repairers, and to prevent unnecessary work for makers. At first a paper questionnaire was made to formulate a list of relevant questions. Then the InstaCAD concept was created, an app that guides the repairer through their part of the 3D printing process.

Physical layer: 'Manual 3D scanning'

Makers who are capable at CAD are quite rare, and are not always locally available. Therefore it would benefit repairers if they could digitally communicate part dimensions and geometry to makers. Scanning a small part accurately can't be done easily or cheaply, that is why a new, hybrid 3D scanning and measuring technique is developed in this iteration.
Almost everyone can take digital photos with their phone nowadays. Even a mediocre phone camera records a significant amount of information about its subject. Enough information so that the overall geometry of an object can be correctly interpreted by a human. Quick iterations of photo-modelling methods in combination with rulers and lasers as a reference showed that extracting measurements from these photo's yields inaccurate results, due to parallax, lens deformation and incorrect edge detection. A more reliable and cheap measuring tool is the caliper. A rig was prototyped to attach a vernier caliper to a smartphone for quick capturing of measurements. It was tested by recording a part's dimensions and letting someone else reconstruct it in CAD.

Communication layer: local collaboration

At the second Repair Café session I temporarily installed myself as an in-house maker with my 3D printer, assisting the repairers by printing parts for them. I learnt that although I didn't announce my plan beforehand, there was just a little demand for 3D printing, but they mostly resulted from the repairs themselves. Specific demand for part production is not yet present, because it hasn't been an option until now.

Main insights

This first iteration was the first time the concept took shape in the form of prototypes. The first prototype with the caliper gave very positive results, but also showed lots of inadequacies. The Vernier caliper prototypes worked but were inferior to a digital caliper because the scale is very difficutl to read. Also there wasn't much added value of attaching it to the phone, making it rather cumbersome.
The first 3D printing session at the Repair Café showed that there was some demand that resulted from other repairs and that small parts could indeed be printed in this short time span. However time will tell if more specific 3D printing demand can grow if more people learn about it.

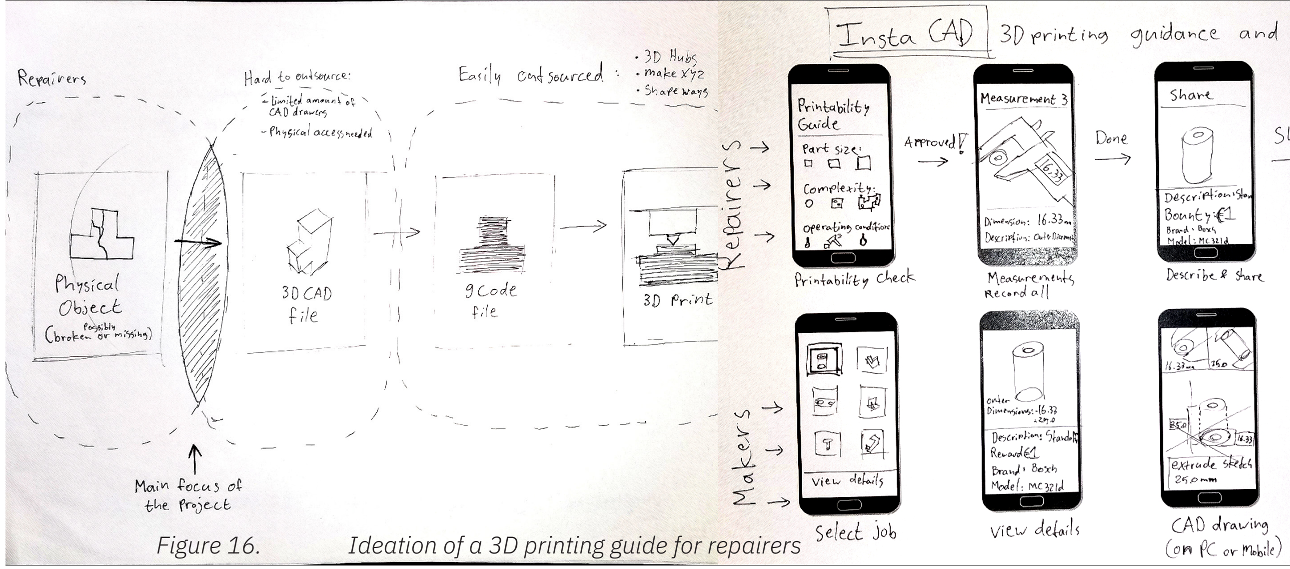


Figure 16. *Ideation of a 3D printing guide for repairers*

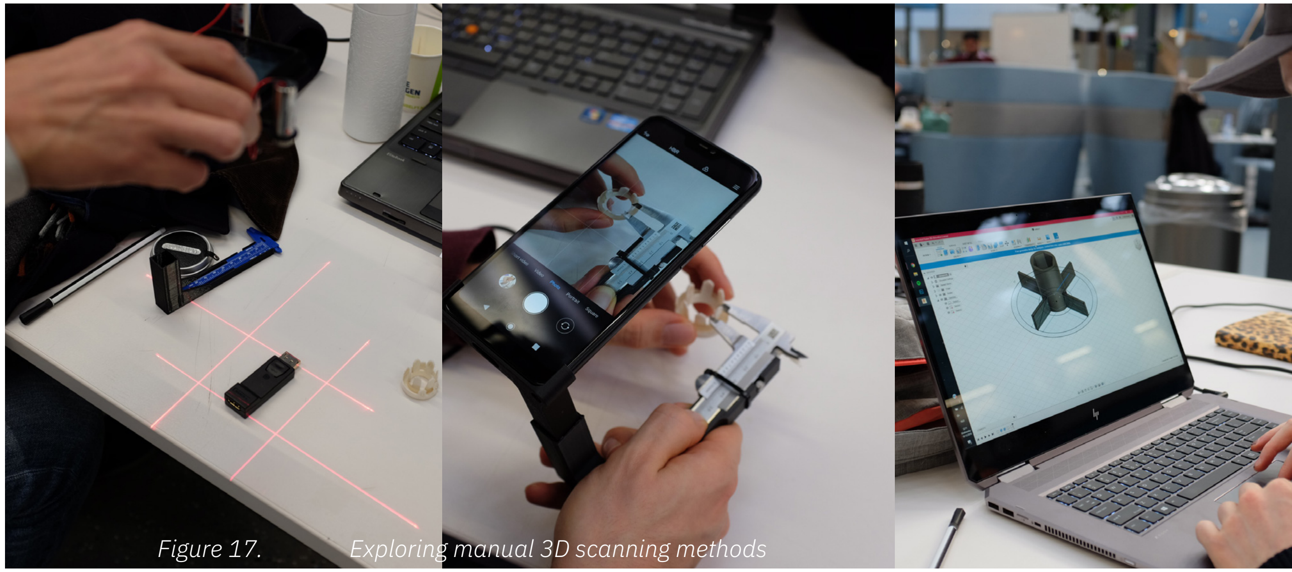


Figure 17. *Exploring manual 3D scanning methods*

Figure 18. *First 3D printing session a the Repair Cafe*

Second iteration

For the second iteration a three part concept was prototyped and tested with the repairers at the Repair Café. It consisted of a mockup app, a caliper with a bluetooth phone button and a phone standard, also me and my 3D printer were on the scene ready to model and print requests. A more detailed report can be found in appendix L.

Information layer: 3D printing guide

A mock-up 3D printing Guide app was made using Google forms and tested by repairers. The app asks questions such as the value, size and complexity of a part. The app then gives an advice on the “printability” of the part and wheter to continue.

Physical layer: Letting repairers do the scanning

A measuring station was prototyped that enables repairers to measure and photograph their parts for reproduction by a maker. The “Cybercaliper” was created by attaching a Bluetooth shutter button from a selfie-stick to a digital caliper. This enables the repairer to take a measurement and record a photo at the same time on the phone while only holding the part and the caliper.

Communication layer: Embodying the maker

Embodying a 3D printing ambassador at the Repair Café for the second time. There were more print requests, since people were expecting me, they brought print jobs from home. I also installed myself more centrally so that they were visually reminded of my presence during their work.

Main insights

The tests with the app and the calipers showed that all of the repairers were able to use both the tools. The quality of the photos varied slightly among repairers, some were very thorough and some were more sluggish. Sometimes things were unclear and they had to be guided to the next step. More tests need to be done to check whether most repair volunteers can use this tool without too many problems, and without personal guidance, this will be done in iteration 3.

Splitting the workflow

At this point it was clear that the 3D printing workflow could be split between measuring and modelling, and between printing the final installation. The three tasks modelling slicing and printing can best be left to makers because they are the only ones skilled enough for these steps.

Figure 19. Testing the 3D printing guide mockup app at the Repair Cafe

Figure 20. Testing the manual 3D scanning at Repair Cafe Delft

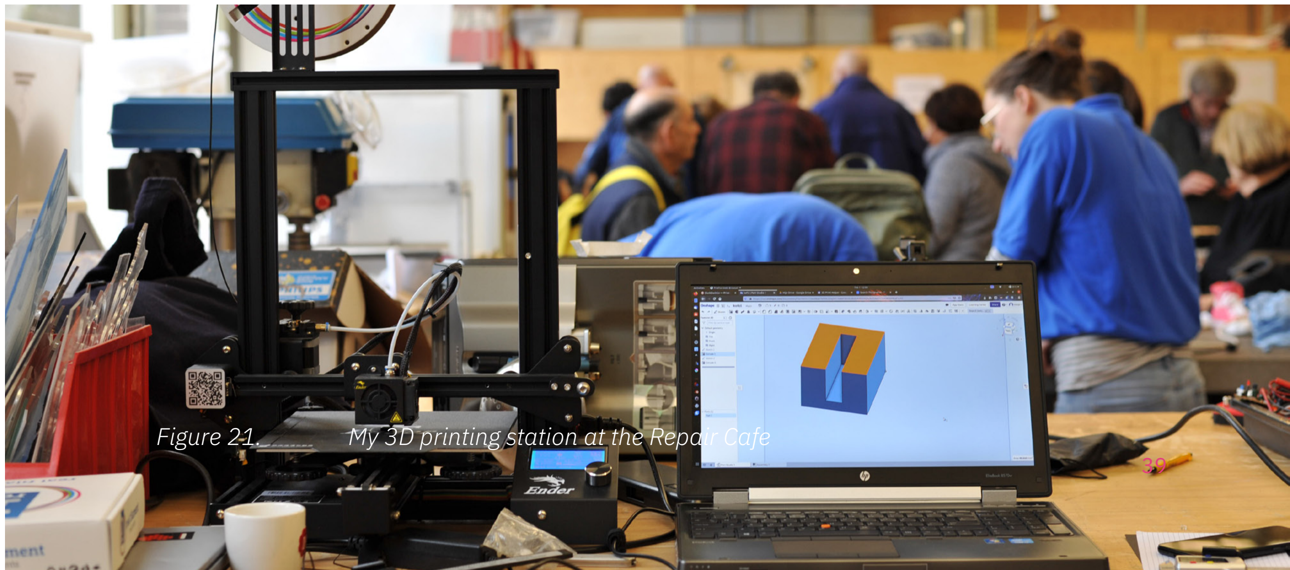


Figure 21. My 3D printing station at the Repair Cafe

Third iteration

The third iteration only got minor adjustments compared to the second concept. Multiple dedicated Bluetooth calipers were prototyped in order to do tests with multiple people. The goal of this iteration was to gather feedback from a large group of makers and repairers. In order to do that, a visit was made to a special 3D printing for repair event at a FabLab in Brussels and a repair challenge at a FabLab in Liége. A more detailed report can be found in appendix M.

Presenting the concept

The concept was presented to a group of makers and repairers. The goal was to teach them about using digital fabrication techniques for repair. The questions and feedback were gathered and used for streamlining the presentation of the concept. Furthermore a mailing list was created for enthusiasts who can later be approached to perform tests and join the online core community.

Focus group session

A focus group style test was done after the presentation. A group of around ten people were asked to pair up and test the connected caliper set-up. They were asked to follow instructions on an app and manually scan a set of objects and upload them in a mock-up phone app. Their reactions as well as the way they conducted the test were analysed.

Individual tests

In Liége a group of around eight people from the repair and maker community were individually tested. They were given the same task, manually scan a set of objects so that a maker could reproduce them. Some of the objects were actually modelled and 3D printed during the session by the makers.

Main insights

The reactions from the groups were very encouraging, they were enthusiastic about the concept and most of them joined the mailing list. The concept performed reasonably well during the tests, the results from the tests were in many cases usable, but their quality differed. It was encouraging to see how many users intuitively knew how to use calipers, but some made rookie mistakes such as only using the outside jaws. More focus should be put in a clear tutorial to make sure that novice users are told explicitly what to do. Another finding was that the language barrier is a real issue for European repairers. Most repairers are of an older demographic who can't speak english well, this must be taken into account when launching a concept in European Repair Cafes. For these users it's best toranslate all the instructions in their mother tongue.

Figure 22 Workshop and presentation at the FabLab in Brussels

Figure 23. Testing the concept in a group session and individually

Figure 24. Collaborating with makers by letting them do the 3D printing

Fourth iteration

The measuring aspects were tested thoroughly in previous iterations. In the fourth iteration more focus was put on the communication with repairers. Once again I installed myself with my 3D printer in the Repair Cafe. A more detailed report can be found in appendix N.

Becoming the repairer

In order to test the final concept, the maker was once again embodied by setting up a 3D printing station at the Repair Café. A closer look was taken at what it's like to be a repairer at the Repair Café. This time the requests from the clients went directly to me and repairers minded their own business. This was another perspective that was not yet explored because the communication with the client was more direct without the repairer in the middle. It gave better insight into why repairers make certain decisions while they are pressured to a certain extent by the client to fix it quick and fast. Although some repairers can deal with this pressure than others, this does affect decision making such as how long the repairer is willing to wait for a 3D print.

Rising demand

At this Repair Café session it became clear that the demand was much higher than at the previous ones. This shows that the news of "A 3D printer for printing spare parts" can spread and attract significant demand from the visitors of the Repair Café. Eventually seven 3D printing requests were made of which five were completed.

Main insights

The communication with repairers should be informal and allow for many different types of info sharing. Sharing personal information of repairers and makers may incentivise both parties to have more commitment. At the Repair Café Delft the demand is rising, therefore it will make sense to install a maker with a 3D printer in order to get quicker repair times for simple parts, next to having more complex jobs done via the online platform. A clear distinction has to be made between repairs that are fixed on the fly, and repairs that require more time to fix. This time may be necessary to wait for a spare part to be ordered or 3D printed.

Doubling sessions

At the Repair Cafe in Delft the sessions are going to be doubled from once a month to twice a month. This will make the inbetween period a more manageable two weeks instead of four. This means that it will be more acceptable to let clients wait for two weeks on a part. It may also cause repairers to be less pressured into fixing things on the fly.

Figure 25. Repair requests completed by 3D printing at the Repair Cafe

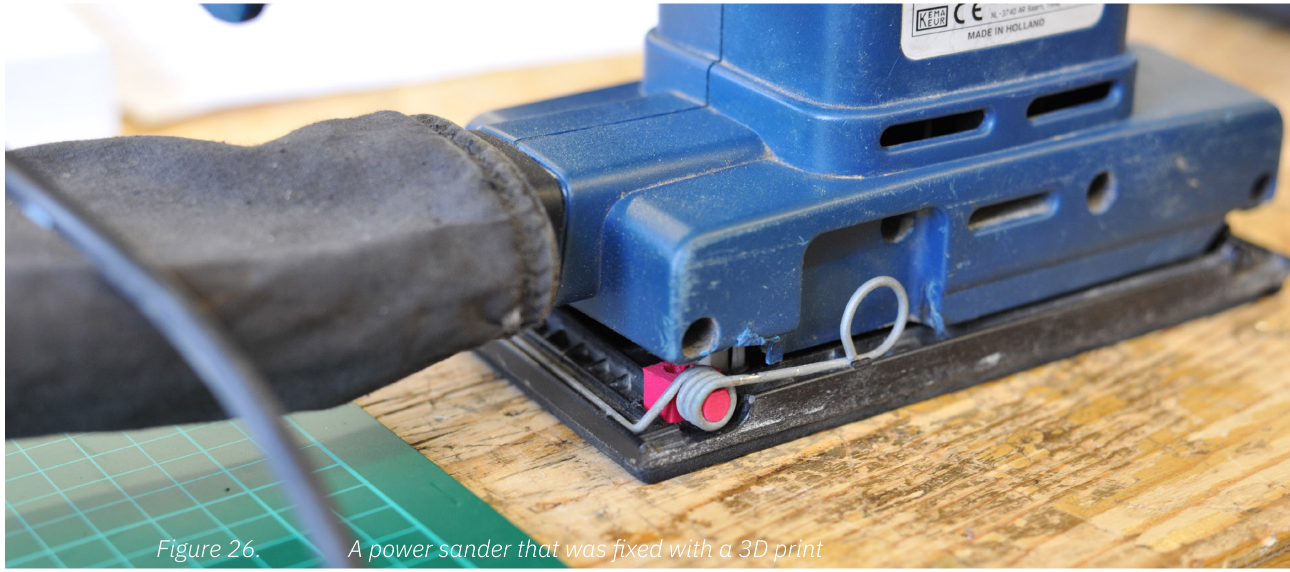


Figure 26. A power sander that was fixed with a 3D print

Figure 27. Me as a repairer at Repair Cafe Delft, armed with a laptop and a 3D printer

Final concept

The final concept was defined by combining several elements of the previous iterations into a product service system. The parts were selected by comparing how well the iterations fulfill the requirements.

The systems works as follows (see figure 28):
- A repairer needs a spare part and wants to use 3D printing for this.

Information layer
- The repairer checks via the platform if this part could possibly be printed.

Physical layer
- He makes a ‘manual’ 3D scan using a regular caliper or the CyberCaliper. With the CyberCaliper a rapairer can easily take pictures by using the shutter button on the caliper itself. This way he does not need to touch his phone and has both hands available to do the measurements.

Communication layer
- After taking all the measurements and documenting them by taking pictures of the part and the caliper, the repairer uploads all of it to the digital platform along with a description of the request.
- On the platform, a maker can look for projects that he is interested in and help a repairer by creatinga CAD model to fulfil their request.
- (optional) If the request needs clarification or additional information, the platform provides a way for communication and feedback between the repairer and maker.

Physical layer
- After a repairer checked and approved a CAD model the maker can slice and print the part. (If a repairer has a 3D printer, he can of course also choose to print the part himself)
- After the repairer has received the part he can inspect, adjust and smoothen it and of course then finish the repair.

Communication layer
- (optional) The repairer can of course share the finshed results with the maker via the platform.

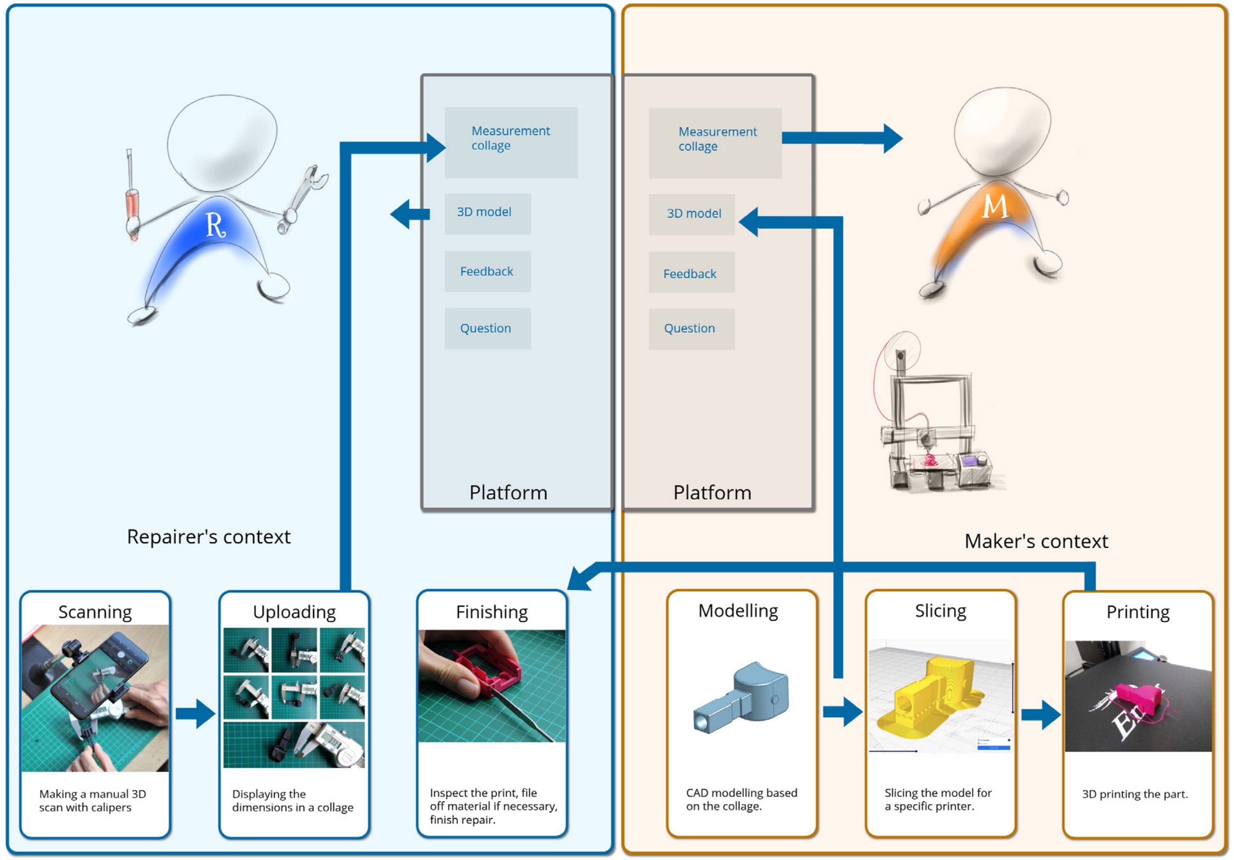
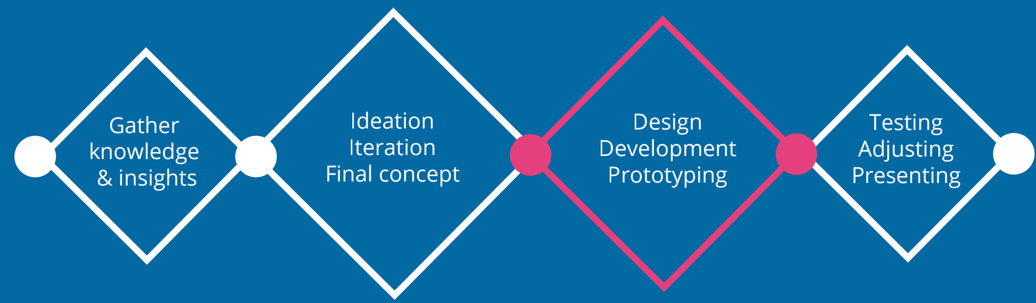


Figure 28. Final concept visualisation

4. Prototyping



This chapter shows how the final concept is translated into a more defined system. Prototypes are created of the two most important parts of the system that will be used to validate the concept later.

CyberCaliper toolkit prototype

A physical prototype of the CyberCaliper was built in order to validate the technical feasibility of the concept and with the intention of testing the workflow of the caliper connected to an app. However the physical tests were cancelled due to the Coronavirus and the focus was put on the online platform. The prototype was used to create a digital representation online that could be shown to experts.

Prototyping the hardware

A hardware prototype was built by taking a digital caliper and designing a new case that houses additional electronics for connecting to the phone and interpereting the data from the caliper. Most calipers have a data port on the PCB which can be read using an Arduino. For the prototype an arduino micro was used because of its small formfactor and open source nature. An HC-05 Bluetooth module was used to send the data from the Arduino to the phone. More details about the prototype can be found in Appendix O.

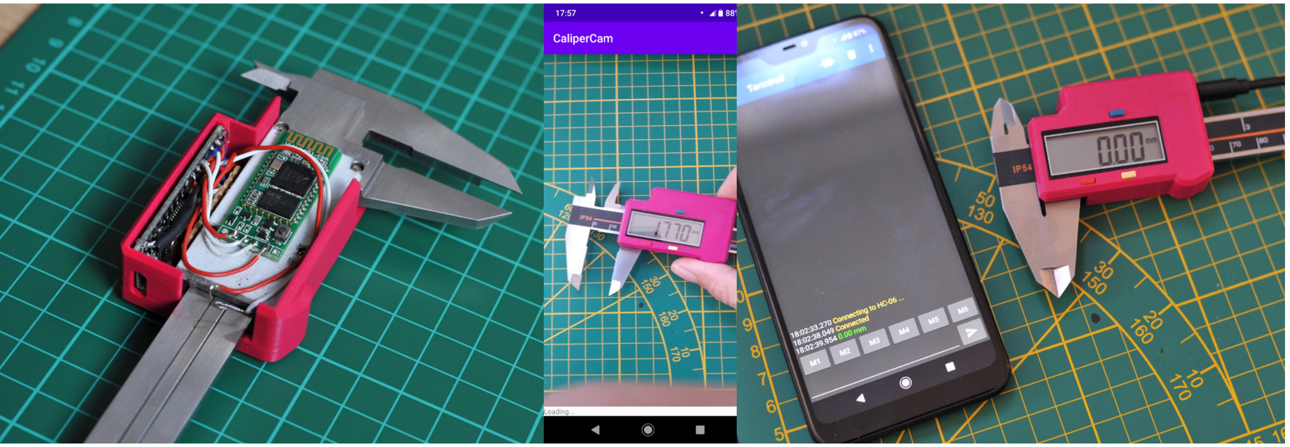


Figure 29. CyberCaliper and CaliperCam app prototype

Prototyping the software

A first attempt was made to build a mobile app ‘CaliperCam’ that connects to the CyberCaliper over Bluetooth and embed the measurement data while taking photos. Parts of the app were working when the decision was made to abandon this part of the prototype and focus on the online platform. This was done because the physical tests were cancelled due to the Coronavirus.

Digital representation of the toolkit

A digital representation was made of the toolkit in a web-shop style way. This was used to get feedback from experts by showing them the website, see chapter 5.

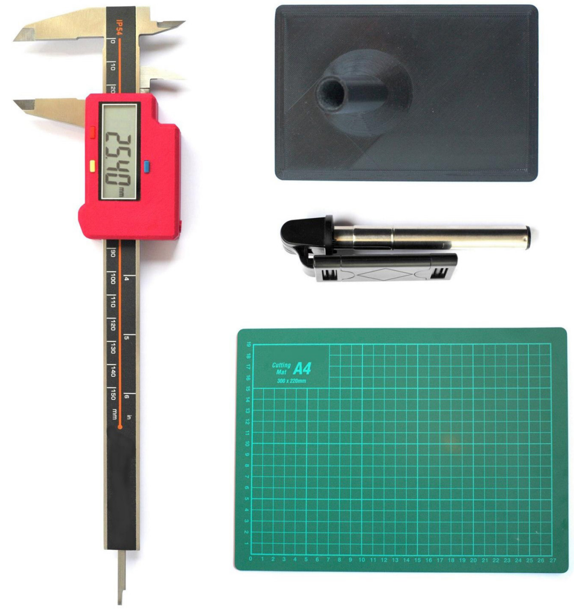


Figure 30. CyberCaliper and measuring accessories

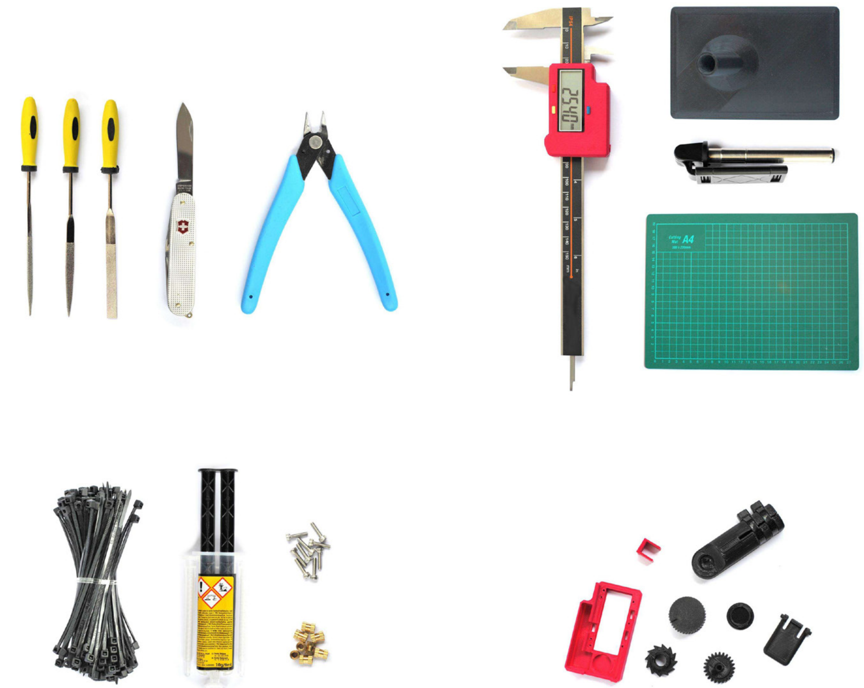


Figure 31. Starter’s toolkit with CyberCaliper (upper right), finishing tools (upper left), fasteners (lower left) and samples (lower right).

MakerMarket platform prototype

In this online marketplace repairers and makers can interact to design and fabricate spare parts for repair. This website can be viewed at: www.cybercaliper.com

Posting requests

An online prototype is developed that enables quick testing and iterating for the evaluation phase in chapter 5. The prototype consists of a marketplace style platform that allows repairers to post CAD modelling and 3D printing requests.

Comment section

After the repairer posts a request the makers are able to respond in the comment section under the post. In this area a dialogue is supposed to facilitate the collaboration between the makers and the repairers. It enables participants to share text as well as view and share images and 3D STL files.

Tutorials

For the new users to get acquainted with the website and the envisioned process of creating measurement collage, an Instructable tutorial was made. It can be found at: https://www.instructables.com/id/How-to-Make-a-Manual-3D-Scan-With-Calipers/

Tools

The tools were displayed on the website in order to portray the concept in a coherent way to experts.

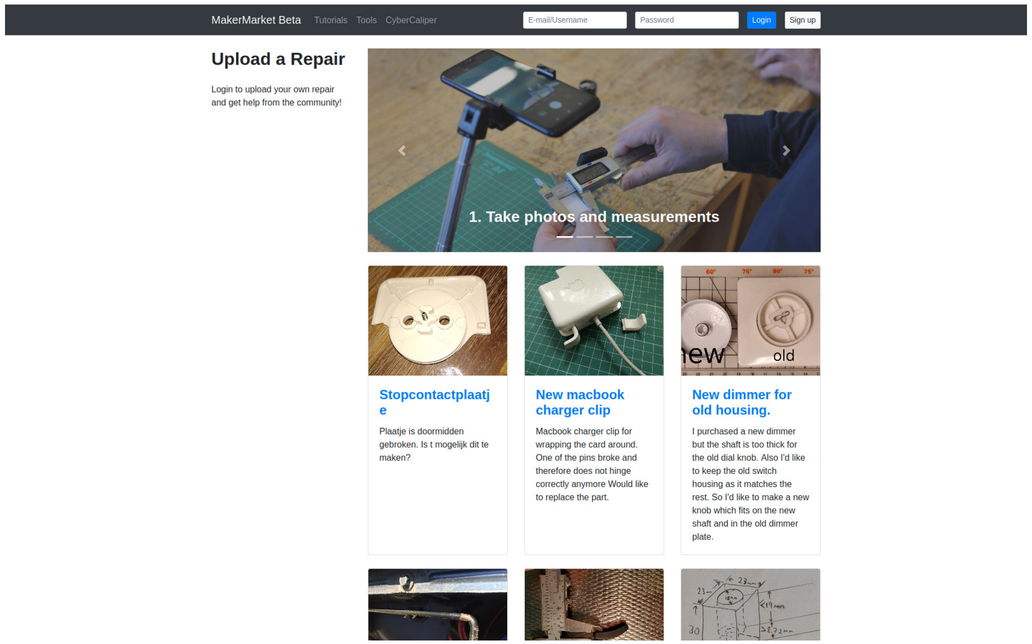


Figure 32. MakerMarket - Home page which shows an overview of make requests posted by repaires

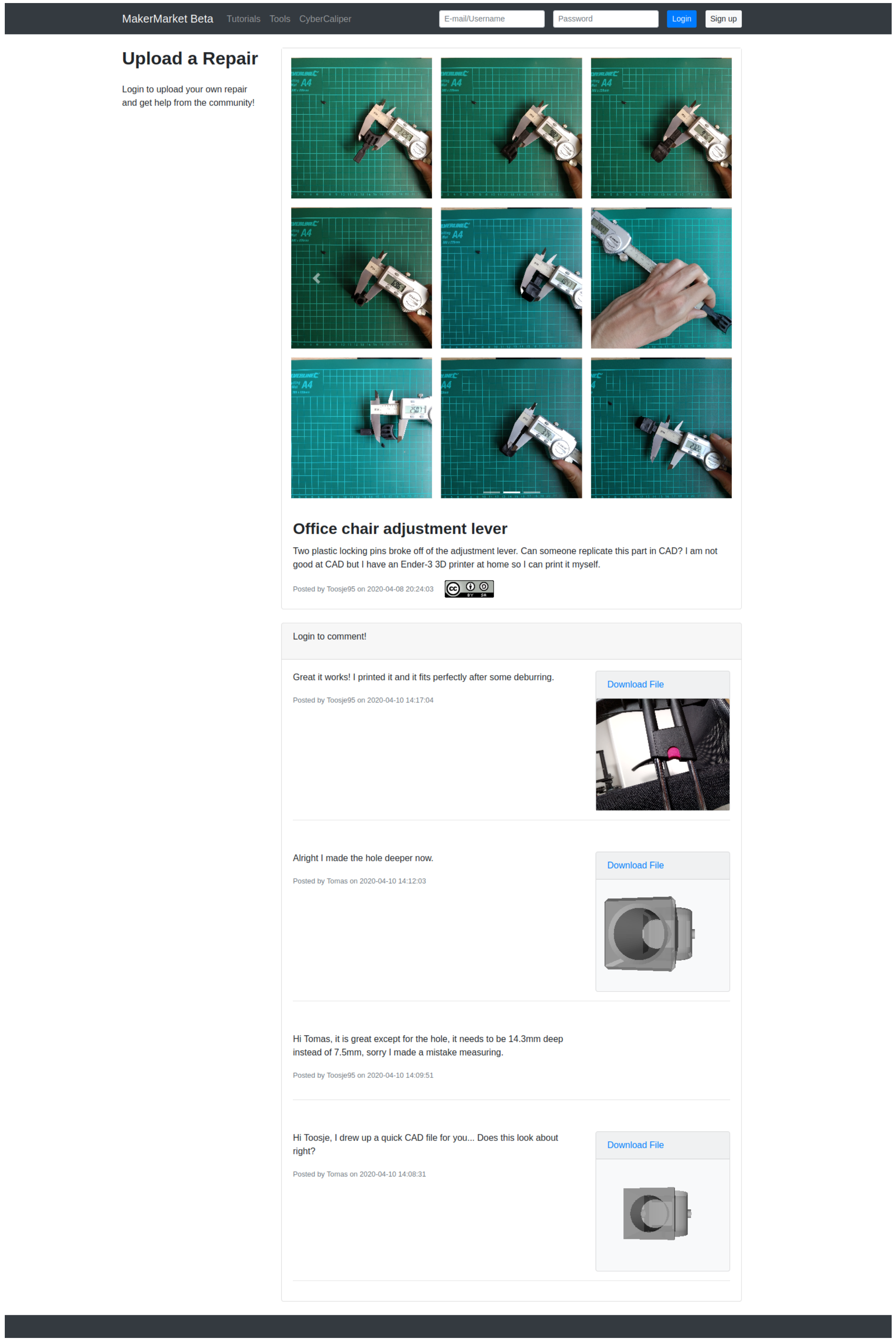
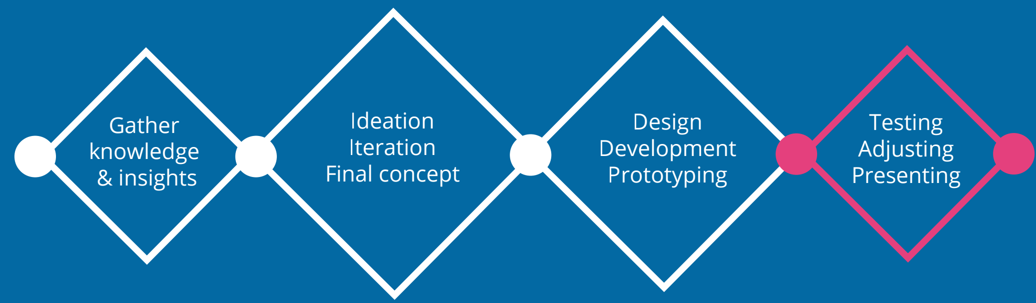


Figure 33. MakerMarket - Example post including example comments from a maker

5. Validation



In this chapter the prototypes are validated. The design choices that were embodied in chapter 4 are tested before making final adjustments and recommendations. The test approach and results will be discussed in this chapter as well.

Toolkit expert validation

After creating the toolkit prototype, the design elements were proposed to an expert in the field of 3D printing for repair. In order to validate the concept and get feedback on the details and elements of the toolkit and it's purpose.
The expert, Anika Paape has co-founded a German 3D Printing for repair program: 3D-Druck & Reparatur. An interview was prepared, see appendix Q for the full interview plan.

The concept was explained to the interviewee followed by a number of questions. She understood the purpose of the overall concept and the maker market. Although the purpose of the toolkit was less clear. She didn't know who was the target user of the toolkit.

Main insights

- Many important decisions are in line with the expert's experience.
- Leave the CAD modelling to makers, don't try to teach the repairers CAD.
- Low end or high end 3D scanning are not practical for repair.
- The overall concept and some of its elements aren't clear at first glance.
- It's not clear how people can get a cybercaliper.
- The concept is not clear at a first glance.
- Generic tools are not necessary because most repairers have them already.
- If you want to attract makers they need to be challenged with creative projects.
- Installing an app can be a hurdle for the average repairer, a website is easier for them.

Main Recommendations

Keep going in the direction of enabling repairers to get support from makers and using calipers instead of 3D scanning, this is the most painless and straightforward way according to Anika.
The home page of the website should be much more self explanatory, explaining the concept through visuals and showing why which tools are needed and where they can be found.
Don't include generic things in the toolkit, what most people already have, or give people the option to include or exclude items.
In order to motivate makers they need to be challenged. Challenge them by letting them build their own CyberCaliper or organise a creative redesign challenge for repair.
Don't make an app mandatory for using the system. A website that works on desktop and mobile can be sufficient and is easier for the older repairer demographic to use. The app can be an extra that is only used for connecting to the CyberCaliper.
The full insight list can be found in appendix Q.

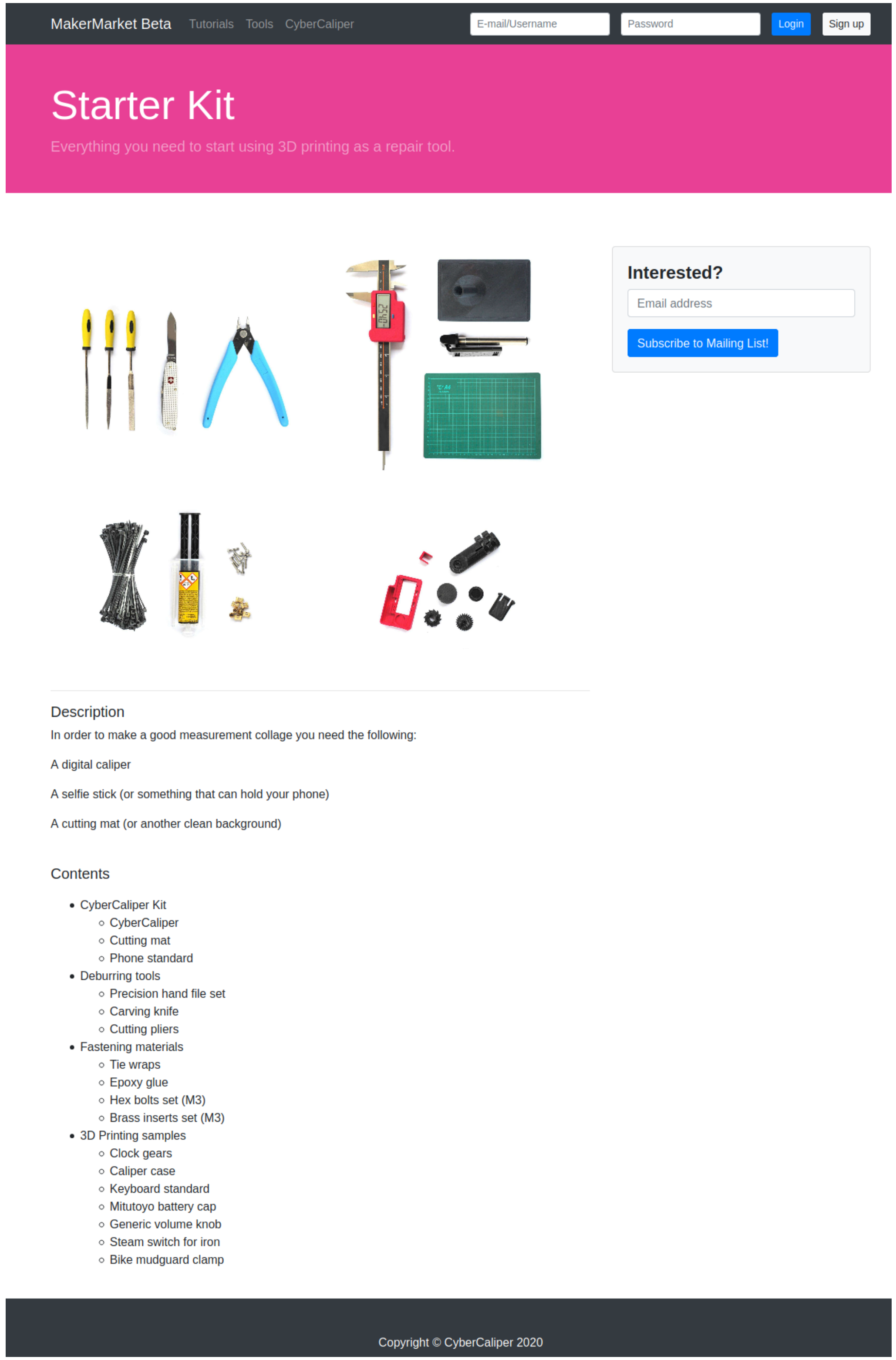


Figure 34. Representation of the toolkit as shown to the expert

Online platform user validation

Main goals

The online prototype was tested with a small group of repairers and makers. The goal of the test was to validate the validity and completeness of the concept. Another goal was to validate the usability of the current prototype.
The repairers were asked to post an object or part that they thought was fit for 3D printing on the website. Afterwards some makers were asked to reply to the posts, to give advice and to try construct the CAD files. The full test plan and results can be found in appendix R.

Main insights

A more detailed insight list can be found in appendix R.

Varying measuring and description techniques.

Some repairers had their own way of communicating the object geometry and measurements. Requests came in to use other forms of measurement instead of a caliper such as using LEGO, a coin or a ruler as a reference. One of the repairers included a paper sketch on which the desired object and its dimensions were sketched. Others however did follow the tutorial precisely and created a caliper collage.

Infeasible requests

Some requests were not suitable for FDM 3D printing, such as a part of a stove that becomes hot. These requests were given the proper response by makers not to use regular PLA.

Incomplete measurements

Some of the measurements were incomplete, missing dimensions, context or some description. This lack of information had to be obtained by the makers in order to construct the part.

Commitment and incentives

Many of the repairers didn't respond to the request to take part in the test. This could be due to several reasons. Lack of incentive. Lack of confidence. Lack of time. The first two can be addressed by the design.

Usability issues

Some usability issues became clear when users started to use the platform. The foremost feedback was that repairers can only post 3 images in the initial post. Meaning they need to make collages using external software. This could be solved by letting them upload all their images at once and automatically generating a collage. Another issue was notifying users of new messages and posts, currently not built in. A balance needs to be found between keeping users up to date on their posts without annoying them.

Recommendations

Basic usability issues need to be fixed such as notifying the user of a reply on his post or comment.
Creating a collage should be automated by the platform itself so that users don't need to use external software for that. This will smooth the workflow so that users can upload a large series of images and not worry about creating a collage.
Clearly guide new users through the process of identifying a part, manual scanning and uploading. This will result in more consistent measuring techniques and will eliminate some of the infeasible requests early on. This info should be embedded into the uploading workflow.
Explain why calipers are important for accuracy, and when and where accuracy is needed. Leave an option for people without a caliper to post anyway but explain that high accuracy will not be possible in that case.
Do further explorations into hands free measuring techniques such as video with voice recognition for speaking out measurements.

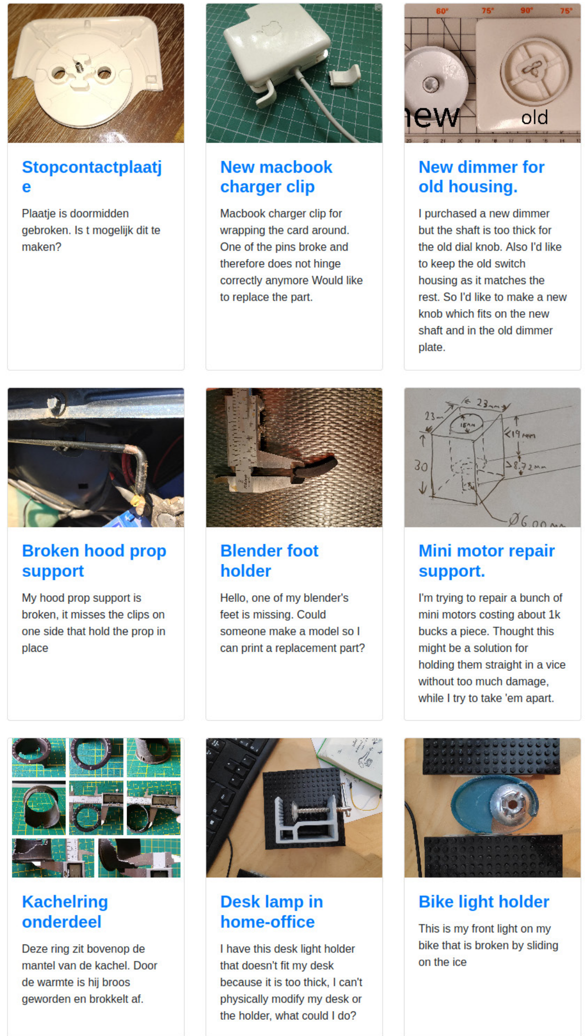
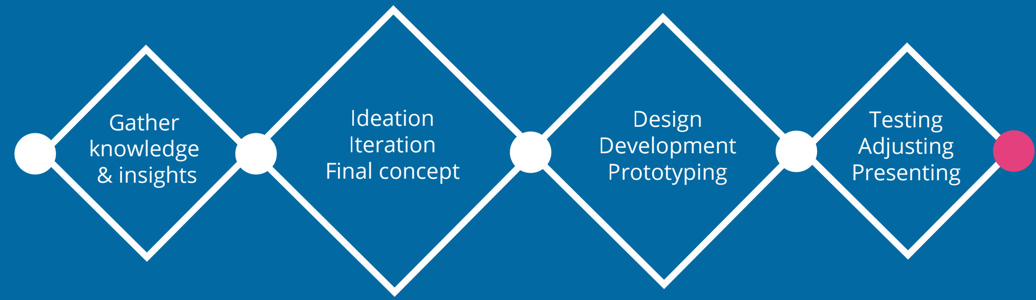


Figure 35. Posts that were made by the participants

6. Final design



In this chapter the final design is proposed for the toolkit and platform. The recommendations from the validation are implemented in this proposal.

Final design proposal

The design has been adjusted according to the recommendations that resulted from the validation. This is the result of those adjustments.

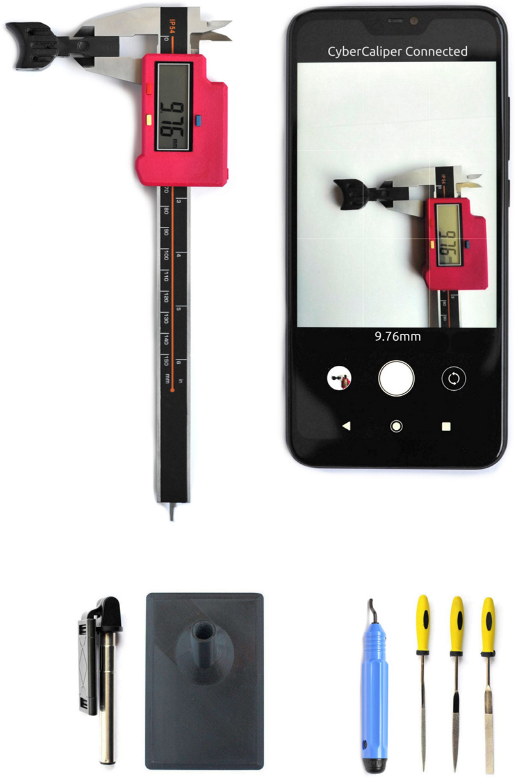


Figure 36. Final toolkit proposal

Toolkit

The toolkit for repairers has been brought down to it's essence. The generic elements have been left out because most users already own these. Instead the focus has been laid on the CyberCaliper the phone standard, and specialist tools for 3D print finishing and installation such as a deburring knife and precision files.

Platform

Based on the evaluation results, together with a UX expert, the online platform was refined. For the details of this session, see appendix S.

On the right the envisioned homepage of the web platform can be seen. This page is meant to welcome newcomers and inform them of the purpose of the site with the top banner. Those who are interested scroll down and can get inspired by the featured posts. Inspired newcomers can then scroll further and find tutorials on how to get started. When they click the pink ' Start Collaborating!' button, they will be guided through the sign-up and uploading flow which can be seen on the next page.

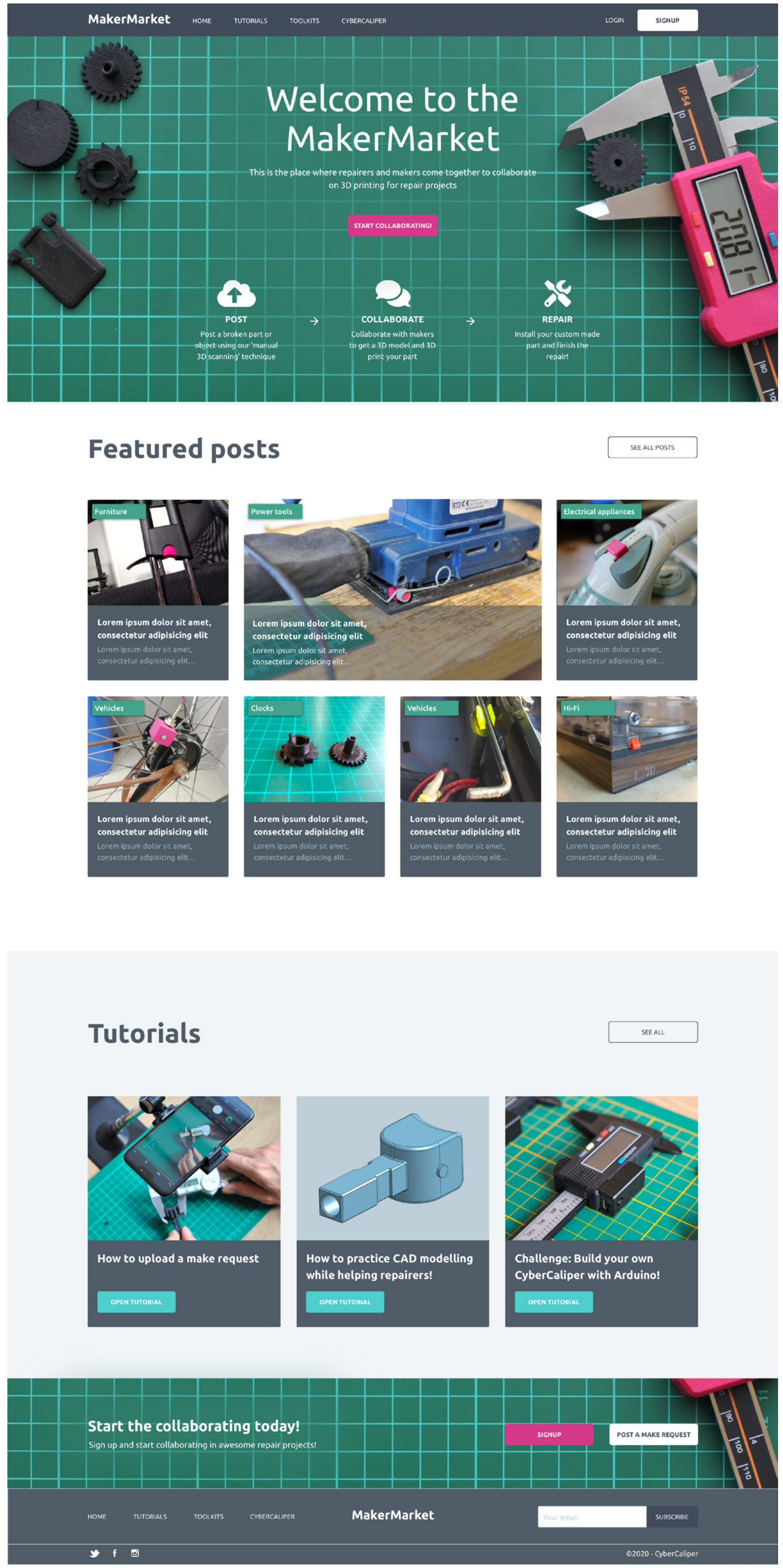
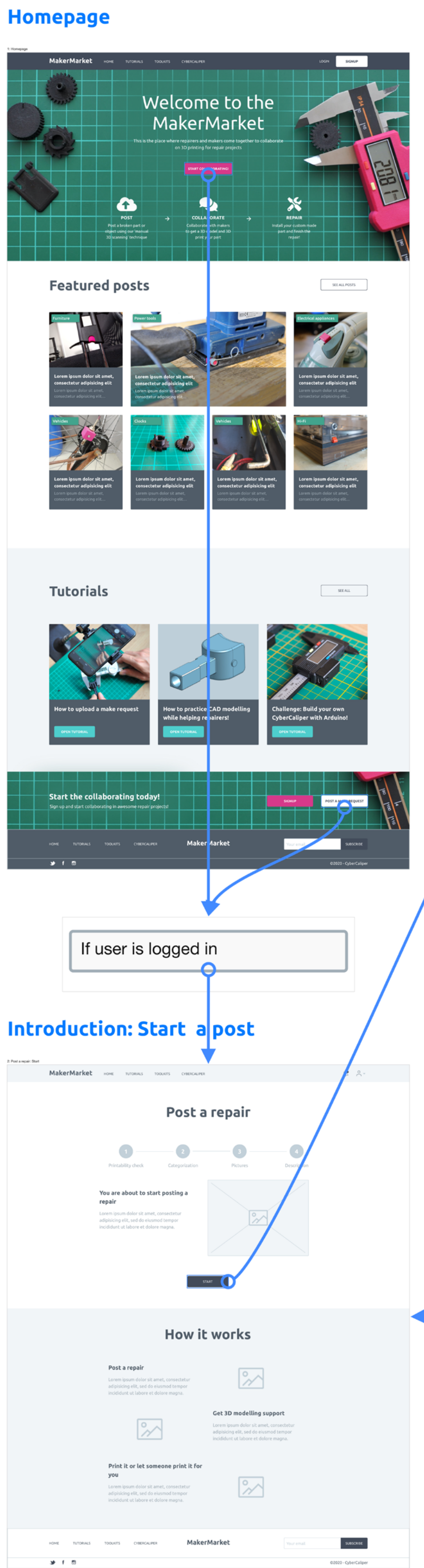


Figure 37. Final design proposal of the MakerMarket home page



Wireflow

By stating the user goals, making a task flow and creating wireframes the recommendations from the validation are implemented and presented in a final website wireflow. This wireflow shows the flow of a repairer making a new post on the platform. The process of creating the wireflow can be found in appendix S. The individual wireframes can be found in appendix T.

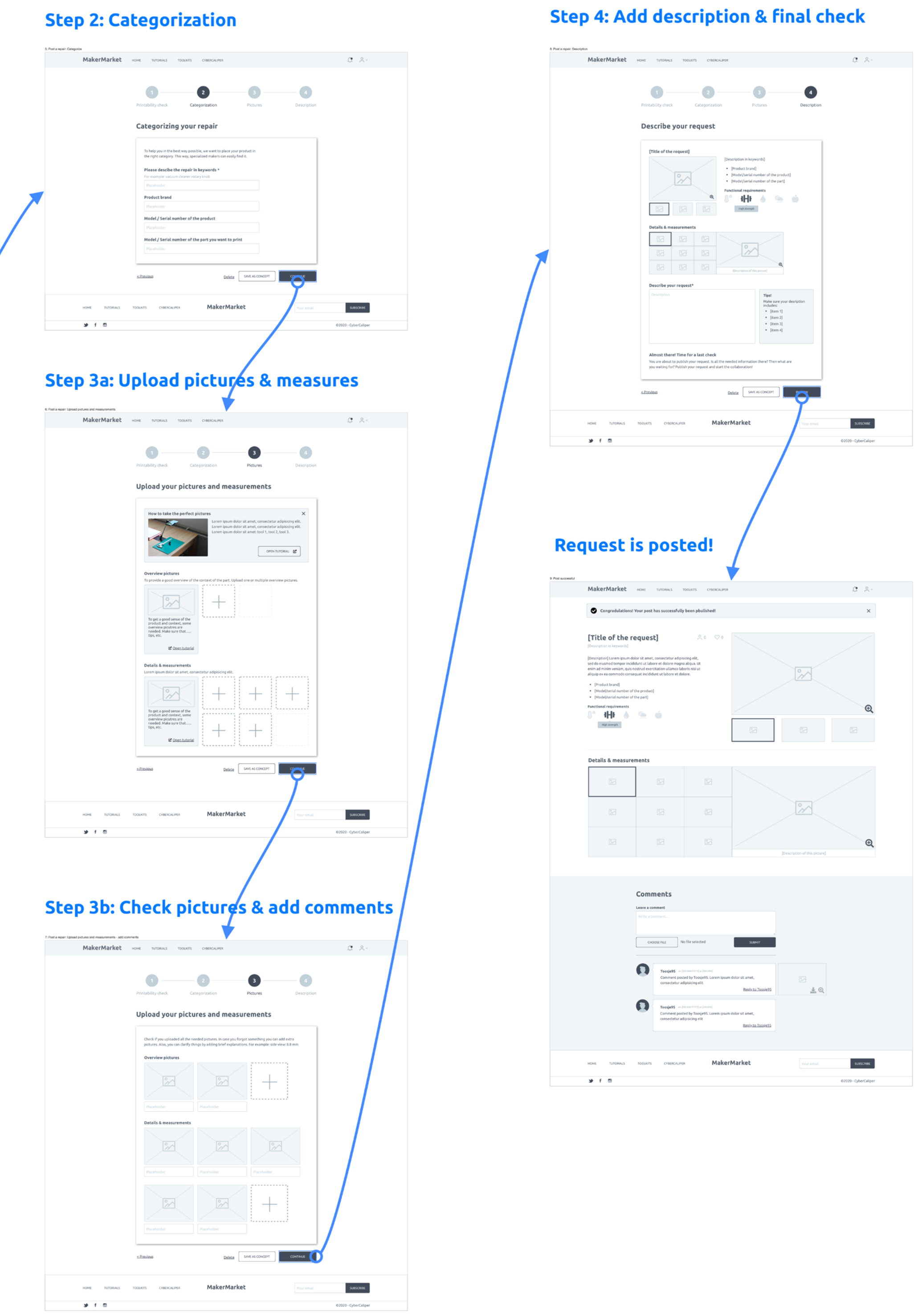


Figure 38. Wireflow of a repairer making a post

7. Conclusion

This chapter concludes the project by evaluating the final design, providing recommendations for further development and a personal reflection on the overall project.

Conclusion

The system as proposed in the final design can technically be developed and implemented, it just needs some dedicated people to continue working on it.

Early on in the project the focus was put on enhancing the collaboration between makers and repairers. Following the tests and interviews with experts this turned out to be a very sound approach, where both groups can get something out of it, if its done without stretching the skills or patience of one particular group.

Another decision that was made early on was to focus on using calipers instead of 3D scanning for turning objects into 3D models. This also turned out to be a good choice after numerous tests with repairers. The caliper is a simple, elegant and intuitive measuring instrument. Most people intuitively know what to do with it, they may not know all the features but those can be taught very quickly. It has a level of straightforwardness, which is needed in the context of this project, that isn't comparable to a complex machine like a 3D scanner.

The proposed concept

The final design has the potential to become the online 'place to be' for 3D printing for repair collaboration. However for this to happen there needs to be widespread adoption among makers and repairers. It is still unclear how many repairers and makers will be interested in joining such a platform and how often they will post a request. These things will all have to be researched further before meaningful predictions can be made. Another aspect is the business viability of the platform. Although it hasn't been the focus of the project, it still is important for a service to support itself and its employees. One way for the platform to generate income is to host a premium version for companies, on this premium version companies can keep posts private and get help from professional CAD designers. This may be interesting for companies with a production line that breaks down because of a part that needs to be replaced quickly. The business viability should be explored further.

Limitations

The main limitation of this project has been to get experienced repairers to adopt a new technology that they are not used to. This will only succeed with repairers who are open minded and willing to learn new things. The Repair Cafe in Delft has proven to be a place with many open minded repairers, however this may be a skewed generalisation because of the high amount of retired engineers in Delft. Further research should be done in the skills and mindset of repairers in other places. Another limitation of the approach has been language barriers, this is a very important factor in Europe. It was encountered in Brussels and Liege, however no solution has been proposed in the final concept. The straightforward solution is to automatically translate the entire platform into the local language. Another option is to create language based communities of repairers and makers, this will result in better communication and less misunderstanding.

Future

Future developments in 3D scanning may make precision 3D scanning faster and affordable. Advancements in phone camera quality and photogrammetry seems likely. This in combination with advancements in AI may make manual reverse engineering obsolete. However, the precision of a high end caliper is hard to beat by consumer grade 3D scanners for the foreseeable future.

Recommendations for further development

Workflow

The proposed workflow was the result of ideation and iteration done in a relatively short timespan. This means that there are more directions that are left unexplored such as letting repairers create (simplified) technical drawings, or creating a scanning technique that displays the caliper measurements like a technical drawing with multiple projections. These ideas may add value to the proposed caliper scanning technique.

Supply chain

The contents of the toolkit that is proposed can mostly be sourced from Chinese manufacturers where the costs are low. However the distribution of these tools throughout Europe or even worldwide is quite difficult. Therefore different distribution methods must be researched, such as doing it together with a partner in repair such as iFixit or an online platform such as Bol.com or Amazon. Another part of the supply chain is the manufacturing and assembly of the CyberCaliper, depending on the sales numbers this may be done in-house, by disassembling and modifying existing calipers, or by creating a completely custom caliper. These options must be weighed before such a decision can be made.

App

The development of the CaliperCam app can be done in-house or by contracting a small number of 'student' app developers, because it is not a complicated app. This app shoud be made open source so that the online maker community can experiment with it and contribute to its development.

Economic viability

The platform, meaning the website, front-end and back-end are rather complex and require regular maintenance, customer support and upgrades. This will require more developers to work on the development over a longer period of time. A platform with many users encounters problems when it's online, such as questions from users, moderating content in accordance with EU Article 13 and managing copyright issues. In order to pay for this there needs to be a steady source of income for the platform. The costs must be mapped before a suitable source of income can be selected. Donations or advertising may be enough to make the platform viable, however more can be earned by providing professional or premium services to companies.

Network effect

The success of the platform depends on the number of users who join it, in that way it will behave like a social media platform. Attracting more users is beneficial for the network effect, in which the platform gains more importance and resources. Further research has to be done to see how such a network effect can be stimulated in the repair and maker community. Using social media influencers on YouTube such as Thomas Sanladerer, Joseph Prusa as ambassadors for the project would give it a huge boost, however this must be timed right and done only when the system is ready for it.

Reflection

This project has been one in which I am very much personally invested. My personal vision is very much aligned with the goal of this project and that gave me immense amounts of intrinsic motivation to do it well. Although I am critical of my shortcomings but ultimately very proud of the results.

At the beginning of the project I set these personal goals:
"Utilising my experience in both making and repairing to facilitate interdisciplinary collaboration." This was a success, I managed to embody the maker and the repairer in me whenever I needed. During test sessions I could play one role while letting the participant be himself. This was also one of the reasons I was so stoked about this project, because I want to help unite these two awesome communities who are currently quite seperated but both of which I very much belong to!

"Applying the design engineering skills I gathered during my studies and internships."
I managed to apply all of my design engineering skills and I managed to focus on the ones that I am least comfortable with such as user research and observations. It was a delight to work with these user groups because they were so enthusiastic, which helped to motivate me to do even more user testing.

"Working with stakeholders and observing their needs, and making use of their experience."
This project has been the most user centered project I have ever done. I recognise the experience of the repairers and makers that I worked with during the tests and I learnt how to amplify their strenghts in the project. Mitigating weaknesses and amplifying strenght is what I try to do by guiding repairers but leaving room for creativity and challenge.

"Managing an entrepreneurial style project with the end goal of publishing the project as an open source hardware toolkit."
The CyberCaliper is going to be published in an open source DIY kit for enthusiast repairers and makers to build it themselves. I loved the entrepreneurial, self-directed nature of this project. It felt like I was working on building a startup, especially when networking with people about it and when building the website the concept really came to life.

If I could do this project again I would try to focus more on the presentation of my ideas and keeping my chair and mentor more up to date. This is an area in which I usually have trouble. I am a thinker and I sometimes struggle to communicate my thoughts to others. This combined with the social distancing didn't help for me because it made the communication more distant and less personal in my opinion.

One of my goals at the beginning was to to deliver something that really benefits repairers and makers. Therefore I am pleased to say that I want to continue working on the implementation of this concept after my graduation. I have always wanted to start a business around a new invention or idea. I personally think this has potential to become a viable business and that is why I will continue to work on it. In the worst case it will be a good exercise that builds my portfolio, in the best case it will become the online place to be for 3D printing for repair!

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