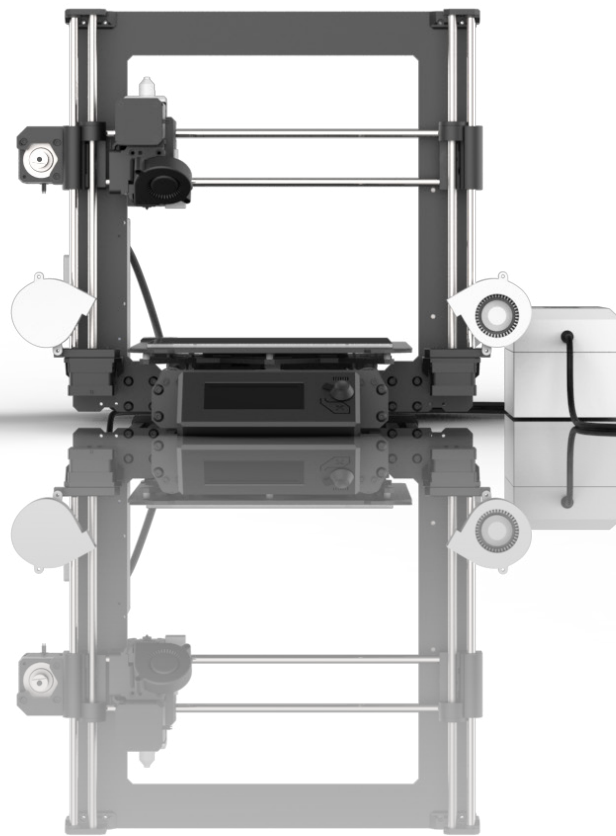


# Design of a 3D printer for healthcare in Sub-Saharan Africa



**Ludo Hille Ris Lambers**

**MASTER THESIS**

Integrated Product Design

Delft, July 2019

# Design of a 3D printer for healthcare in Sub-Saharan Africa

MASTER THESIS

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# Preface

With this thesis, I conclude my studies at the TU Delft. After having done a bachelors in Mechanical Engineering, I feel that I have really found my field during my masters Integrated Product Design.

**I dare to say that this project was a perfect match to my personal interests, skills and core values.**

Therefore, first and foremost, I would like to thank my chair JC for this unique graduation opportunity. Partly by coincidence, we briefly spoke on the phone about the possibility of a 3D printing project focused on healthcare in Africa, and a few weeks later I found myself starting my analysis. JC's enthusiasm and energy never failed to lift my spirits in our byweekly meetings.

I would also like to thank Zjenja, TU Delft's 3D printer expert, my mentor and second member of my supervisory team. He always provided me with new and surprising ideas, and came to my help when I had some difficult technical challenges.

Next, I would like to extend my gratitude to my 3D printing for Africa support team, consisting of Julie Fleischer, Roos Oosting, Mirte Vendel and GYoung Van. They kept a close watch on my project and were always available for support. They also provided me with valuable insights for the analysis phase.

I especially want to thank Julie, and her professor Jenny Dankelman (although we have never met), for providing the resources for this project. Because of them, I was able to build a fully functional prototype. More importantly, they provided me with the means to go on a field trip to Kenya. I feel an immense gratitude for this.

During my field trip to Kenya, I was welcomed warmly by many kind and helpful people in Nairobi and Kisumu.

First of all I want to thank Derrick Mugasia, director of the MakerSpace at the University of Nairobi, as well as Dr. Richard Ayah, director of the Science and Technology Park at the University of Nairobi. They facilitated the opportunity for me to travel to Kenya and work at the MakerSpace. I want to especially thank Derrick for being a friend during my stay, as well as for his help in getting me into Kenyatta National Hospital. At this hospital I was able to get many new insights through interviews and tests with Edwins, Grace and Regina.

I also want to extend my gratitude to my dear friend Ishmael, and his sister Daisy. Ishmael's generous voluntary service was an indispensable help. Day after day, we struggled together to get the prototype to work. Every night, after working long hours at the MakerSpace, he and his sister Daisy took me around the city and showed me all of their local treasures. Because of them, I got to experience Nairobi as it really is, avoiding the tourist's perspective. I am very grateful to both of them for this.

Another good friend I want to thank is Karl Heinz, founder of Nairobi based startup AB3D. He provided me with tangible insights, as well as valuable feedback on my design. I think we will keep in contact, and perhaps even work together on the continuation of this project.

Next, I want to extend my gratitude to everyone from Penn State University whom I had the pleasure of meeting during my short stay in Kisumu.

In particular I want to thank Ben Savonen, co-founder of Kijenzi. The talks we had in Kisumu were eye opening to me, and provided me with possibly the most useful insights from the entire field trip. After the field trip his help continued, as he also volunteered to be one of the experts to evaluate my final design.

I also want to thank Daniel Kats, another member of Kijenzi, for providing me with insights through email contact, as well as Tobias Mahan, co-designer of the Kijenzi printer, who also helped to evaluate the final design.

At the start of the project, I was aided by 3D print enthusiast and inventor Martijn Korevaar, who's enthusiasm and mind full of ideas helped me to really diverge and think out of the box.

I'd like to thank my family, friends and roommates. Joy and Max, for being the Applied Labs dream team. Sam, for allowing me to use his crazy powerful laptop for the final design work. My mom and dad, for providing me with emotional support.

Lastly, thank you reader, for taking an interest in this thesis.

With gratitude,

*Ludo Hille Ris Lambers*

# Glossary

## Acronyms

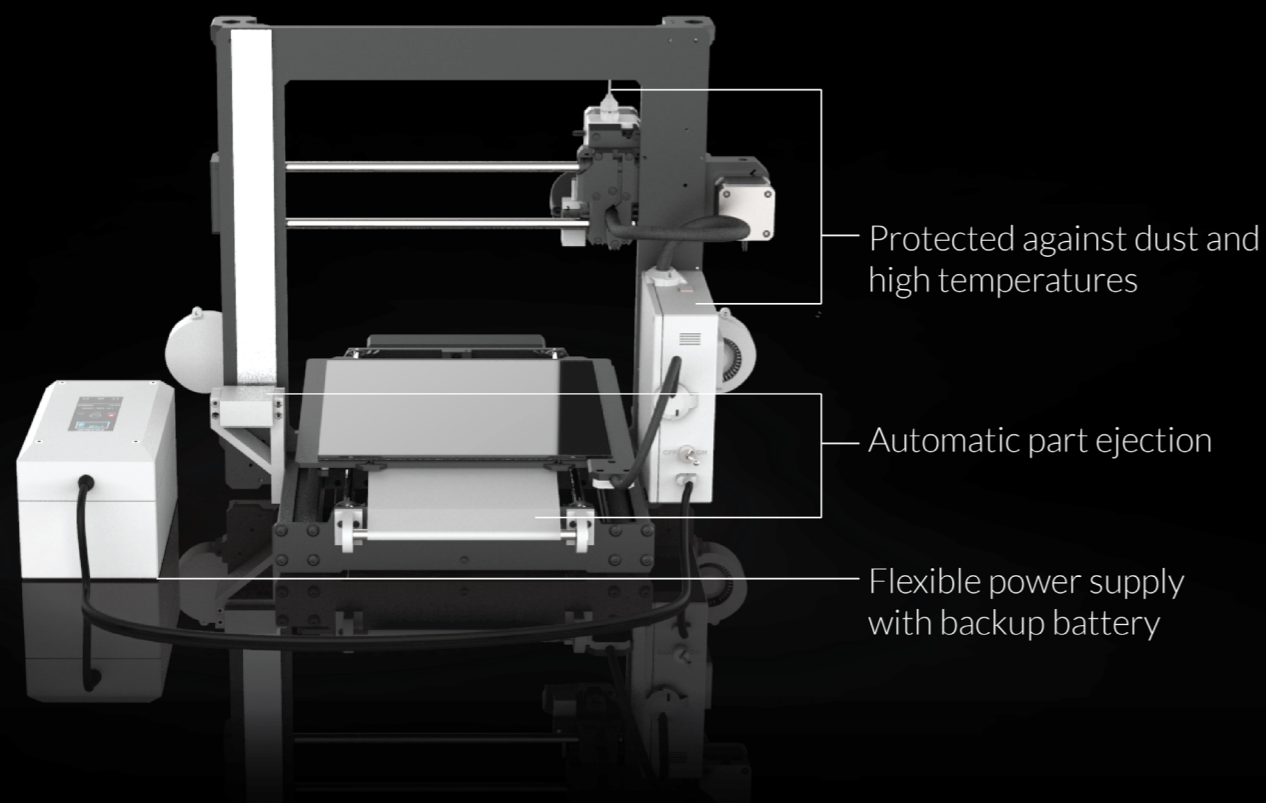
<i>LMIC</i>	Lower Middle Income Country
<i>FDM</i>	Fused Deposition Modeling
<i>ABS</i>	Acrolynitrile Butadiene Styrene
<i>PLA</i>	Polylactic Acid
<i>PET</i>	Polyethylene Terephthalate
<i>TPU</i>	Therplastic Polyurethane
<i>KNH</i>	Kenyatta National Hosptial
<i>IP</i>	Ingression Protection






## Terms

<i>FDM 3D printing</i>	The process of manufacturing three-dimensional objects by depositing successive layers of extruded plastic
<i>RepRap</i>	Refers to an open source 3D printing project aimed at developing low cost 3D printers that can make most of its own parts
<i>Filament</i>	Common jargon for the material used by FDM 3D printers, these are usually general purpose plastics like PLA, ABS or PET
<i>Print bed</i>	Platform that a 3D printer uses to print on, commonly heated
<i>Extruder</i>	One of the most essential components in a 3D printer, used to melt the plastic and extrude it in a thin line
<i>Nozzle</i>	Small metal piece with a tiny hole at the end where the molten plastic is pushed through in the extrusion process
<i>Cartesian</i>	The most common kinematic setup of a 3D printer where motors are used to move the extruder or bed in X, Y and Z direction
<i>Automatic part ejection</i>	System for automatically removing parts from the print bed
<i>Low resource settings</i>	Used to describe LMIC's

# MUUMBA

3D printer designed for healthcare in Sub Saharan Africa



-  Can deal with power outages and surges
-  Protected against dust and high temperatures
-  Able to print continuously
-  Easy to use by anyone with a smartphone
-  Compact for transport, quick to assemble

## Executive summary

With the introduction of the RepRap 3D printers, capable of printing most of its own parts, the cost of 3D printers dropped radically, making it an affordable and accessible technology, even for low resource settings. It is said that 3D printing can greatly increase accessibility to medical equipment in low resource settings because it enables local production and radically reduces costs.

Within the Delft Global Initiative there are several research teams experimenting with the use of 3D printing for local production of low cost medical equipment in Sub-Saharan Africa. They quickly discovered that 3D printing in this setting is not as easy as it might sound. For one, the operating conditions were found to be much harsher in African, than in Western settings. According to researchers from Penn State University, current 3D printers lack in user-friendliness and robustness required to impact rural healthcare.

Therefore, the goal of this project was to (1) identify the challenges for 3D printing in Sub-Saharan Africa, and (2) develop a final design proposal for a 3D printer for healthcare in Sub-Saharan Africa.

### Analysis

The project started with an extensive analysis phase, where Kenya was chosen as a case study of a Sub-Saharan African country. The goal of this phase was to get a deep and qualitative understanding of the context of Kenya, and identify important implications for the design.

This was done through (1) a background analysis, to discover benefits and limitations of 3D printing for low resource settings; (2) a contextual analysis of Kenya through expert interviews, literature research and a field trip and (3) a state of the art analysis to analyze current 3D printers.

The result of this phase was a list of insights, that have direct implications on the design of a 3D printer for this setting. Summarizing, it was found Kenya experiences frequent power outages, excessive dust and high temperatures, making current 3D printers unsuitable for this context.

### Design

Being the core of this project, an extensive amount of time and effort has gone into developing solutions for the identified challenges.

1. To be able to operate on an unstable grid, a flexible power supply with backup battery was designed and tested.
2. To deal with excessive dust and high temperatures, a filament dust filter was developed, as well as a dust tight and cooled enclosure for the electronics.
3. To maintain a maximum printing uptime, a part ejection system has been developed and tested that is able to autonomously remove parts from the print bed.
4. To allow the printer to be used by anyone, without the need for a computer, it was envisioned that controlling the printer from a smartphone application would be the best solution.
5. Lastly, to allow the printer to be compactly transported, a partly assembled setup was found, from where the printer can also be quickly reassembled.

### Final deliverables

#### 1. List of insights

The analysis phase lead to a list of valuable insights that provides a deep and qualitative understanding in the context of Kenya in relation to 3D printing. This can primarily be used for the development of a 3D printer for low resource settings, but might also be valuable for initiatives working on closely related products in a similar setting.

#### 2. Design proposal

During the design phase the insights were used to develop a design proposal for a 3D printer for healthcare in Sub-Saharan Africa. The final design consists of a Prusa i3 printer adapted to fit the context of Kenya. It features a flexible power supply with backup battery, protection against dust and high temperatures, an automatic part ejection system, easy use through smartphone and lastly it is can be compactly transported and quickly assembled.

### Conclusion

The design proposal was evaluated by a panel of experts from Kenya and the US. They rated the final design to fit the intended user and context very well, but also stressed that it could be tailored more to the healthcare sector. The proposal was considered a better solution than what is currently on the market. Lastly, although most of the requirements were met, work is left to be done in several unaddressed areas, of which usability should be the first and primary focus.

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## Chapter 1

# Introduction

In this chapter the field of 3D printing for healthcare in Sub-Saharan Africa is introduced, and the problem is explained. Next, the approach of the project is described, and several fundamental definitions are made.

## Chapter 1.1

## Introduction

*It is said that 3D printing can greatly increase accessibility to medical equipment in low resource settings because it enables local production and radically reduces costs. But is this really as easy as it sounds?*

Within the Delft Global Initiative there are several research groups working towards the goal of making healthcare accessible for all. The primary focus is to develop low cost and accessible solutions for improving healthcare in low resource settings, such as Sub-Saharan Africa. The faculty of 3mE is working on Surgery for All, and is developing low cost surgical equipment that can be locally 3D printed, such as a reusable videolaryngoscope and an electrical surgery unit (ESU). The faculty of IDE is working on Diagnostics for All, and is developing low cost 3D printed diagnostic devices for diagnosing diseases like malaria [1] and schistosomiasis [2] in low resource settings. All of these groups are experimenting with the use of 3D printing as the primary production method, since it is believed that 3D printing parts and supplies locally can greatly reduce costs and lead times, by avoiding complex and inefficient supply chains

These promising opportunities of 3D printing are also highly acclaimed in literature. It is said that 3D printing can greatly increase accessibility to medical equipment in low resource settings through localized distributed manufacturing and by radically reducing costs [3-5]. This

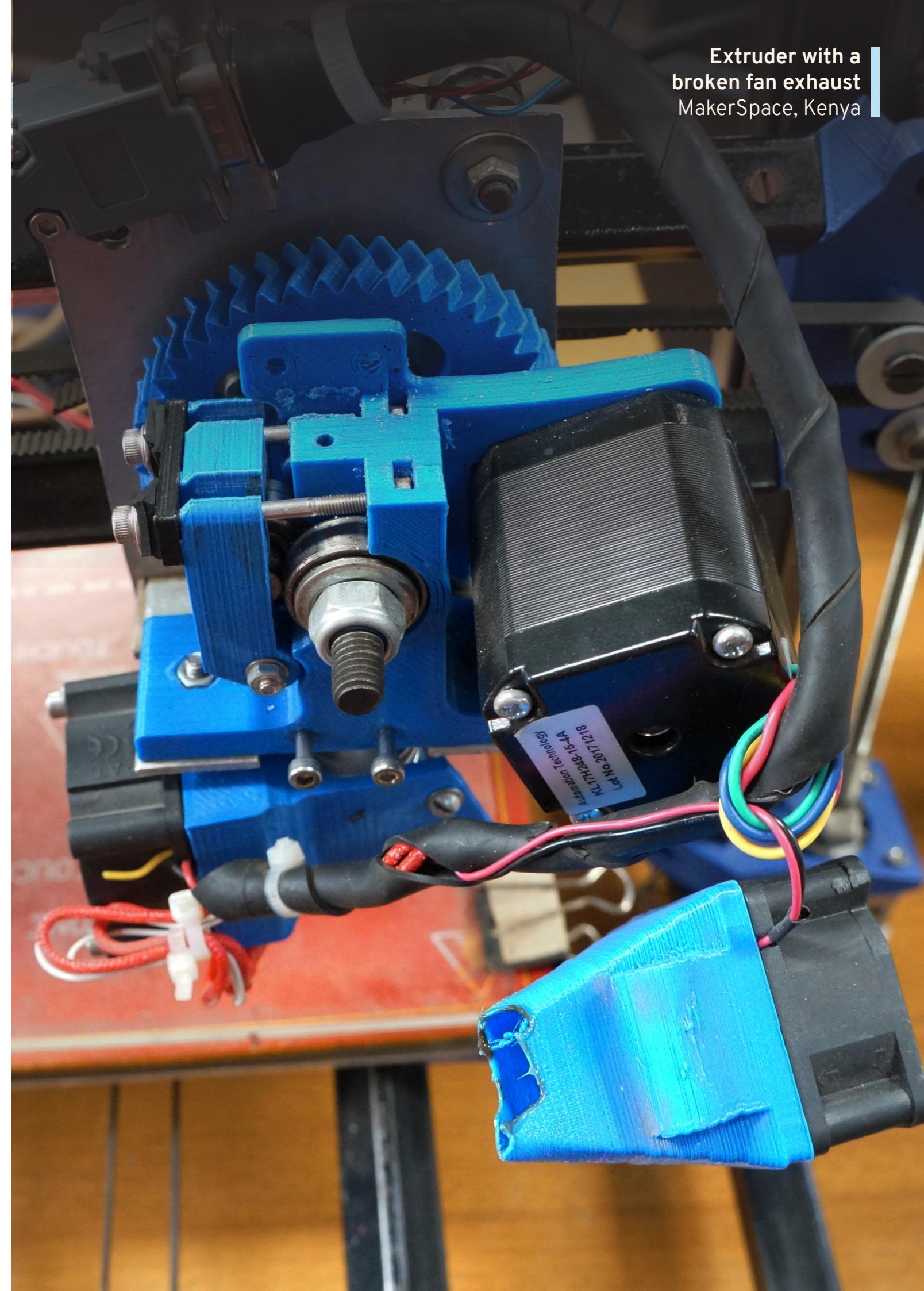
is made possible by the development of the Self-Replicating (RepRap) 3D printer, an open source 3D printer that can produce more than half of its own parts, and costs just a few hundred euro's [6]. These printers have been used to successfully produce functional medical equipment such as clubfoot braces [7], stethoscopes [8] and surgical retractors [9].

It is clear that there are undeniable opportunities for 3D printing medical equipment in low resource settings. However, putting this technology into practice is often not as easy as it might sound. This was experienced firsthand by teams from the Delft Global Initiative, while doing field research in Sub-Saharan Africa. They stumbled upon many potential barriers for 3D printing in these settings. For example, the knowledge level was not sufficient for local independent use of current 3D printers. Also, the operating conditions in Africa were found to be much harsher than in Western settings. Kijenzi, a research team from Penn state university, found during their three month visit to Kenya, that:

**“Current 3D printers lack in user-friendliness and robustness required to impact rural healthcare”**  
- Savonen *et al.* [10].

To use 3D printing as a viable localized production method in Sub-Saharan Africa, these barriers need to be overcome, and this forms the starting point for this graduation project.

Extruder with a broken fan exhaust  
MakerSpace, Kenya

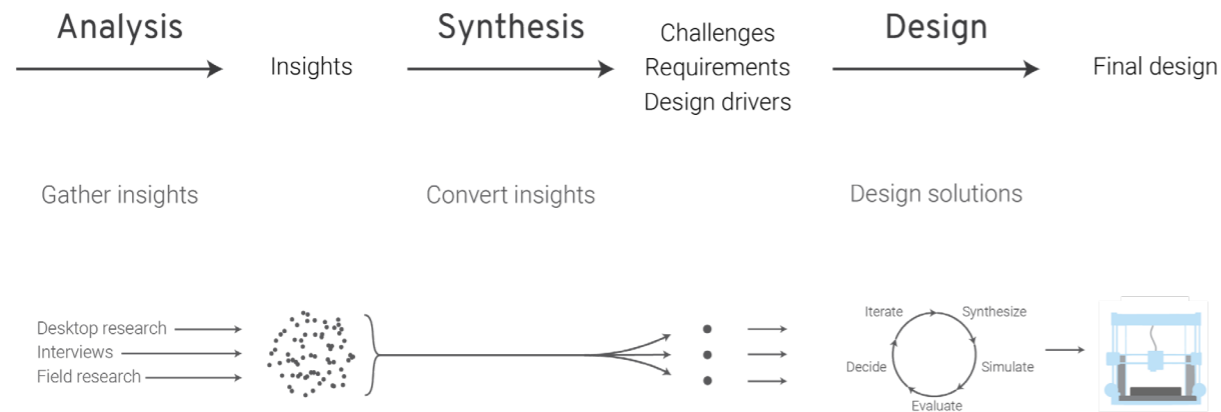




## Chapter 1.2

# Approach

Figure 1: Visual representation of the approach of this project



This graduation project will focus on the design of a 3D printer for Sub-Saharan Africa. Before diving into the specific approach of this project, some clarifications need to be made.

Sub-Saharan Africa is quite big, and therefore too variable to see as a singular design context. Therefore, Kenya was chosen as a case study of a Sub-Saharan African country. Kenya is an excellent example of a LMIC where 3D printing can have a big impact for healthcare. They are well suited to adapt this new technology, as it is considered Africa's fastest growing economy and tech hub. This country was also chosen for more pragmatic reasons, as the supervisory team has good connections with the university of Nairobi, as well as with the earlier mentioned research team Kijenzi, who operate in Kisumu.

Another clarification to be made is in the field of 3D printing. Because the term 3D printing covers a wide range of different technologies, of which many are not relevant for this project, a focus area needs to be chosen. The most relevant field for this project is that of RepRap FDM 3D printers. As shortly mentioned before, RepRap refers to an open source self-replicating 3D printer, known for its low cost, and the ability to produce many of its own parts. Fused Deposition Modeling (FDM) 3D printing, also known as Fused Filament Fabrication (FFF) works by extruding plastic into successive layers, which are fused together to form the final part [11]. This technology is known for its low cost and simplicity [10]. Moreover it can print with virtually any type of thermoplastic material [12].

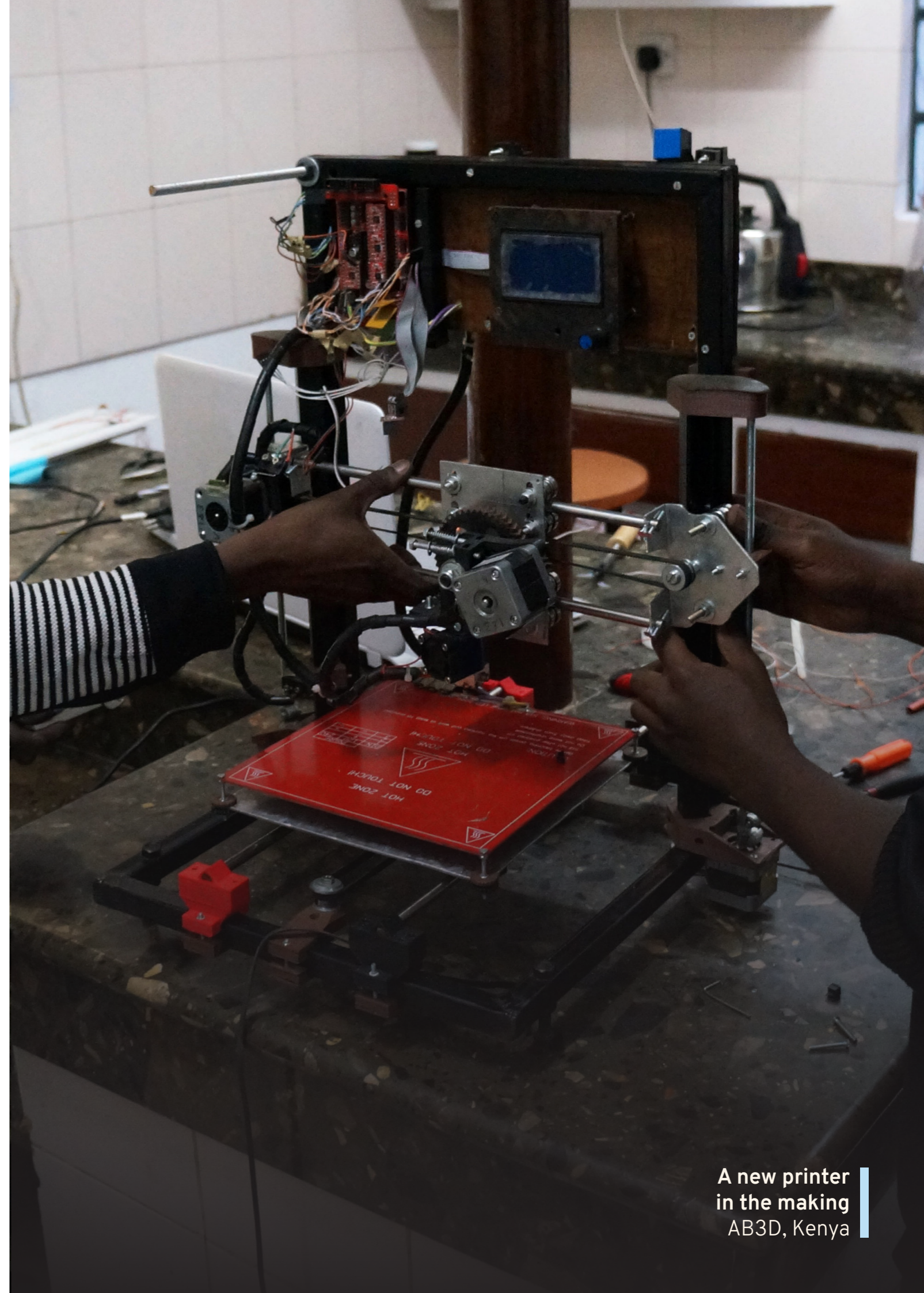
Therefore this is the ideal 3D printing technology for use in Sub-Saharan Africa.

To design a 3D printer for Kenya, it is vital to first thoroughly understand the context. Therefore this project starts with an Analysis phase. The goal of this phase is to get a deep and qualitative understanding of the context of Kenya, and identify important implications for the design. These insights will be gathered through desktop research, interviews and field research in Nairobi and Kisumu.

The next phase, named Synthesis, is focused on combining all of the gathered insights and converting them into a set of design drivers, a list of requirements, and a list of challenges.

These three lists form the fundament of the Design phase. In this phase all of the identified challenges will be taken under consideration, and for every challenge the basic design cycle [13] will be followed until a viable solution is found. The design drivers will be used to evaluate and decide, and the list of requirements will mark the boundaries of the design space. These solutions combined will lead to a final design proposal for a 3D printer for Sub-Saharan Africa.

*Note: This approach has been depicted mostly linear, for clarity reasons. The actual process will be much more circular and iterative, continuously switching between design, analysis and synthesis throughout the project.*





## Chapter 2

# Analysis

The goal of this phase is to get a deep and qualitative understanding of the context of Kenya, and identify important implications for the design.

First a literature review will be conducted to understand and identify the benefits of 3D for healthcare in low resource settings, as well as the limitations of this technology. Next, we will zoom into the specific context of Kenya. Through desktop research, interviews and a field trip, insights will be gathered that have direct implications for the design of a 3D printer for this context. Lastly, the current market of FDM 3D printers will be closely inspected, looking into both the Western market, as well as locally produced printers in Kenya, with the goal of understanding in what aspects current 3D printers are lacking.

## Chapter 2.1

# Background analysis

A literature study is performed to provide a complete overview of how 3D printing could benefit healthcare in low resource settings, and to identify general limitations of the technology.

### 2.1.1 Method

The benefits and limitations of 3D printing for healthcare in low resource settings are researched through a literature review. A total of 30 articles were analyzed, and the most important or interesting findings were extracted.

First, the benefits of 3D printing for healthcare in low resource settings are researched and clustered into the triple bottom line framework [14]. This framework can be used to look at an innovation from three perspectives; people, profit and planet. The main questions that will be researched are:

- 1. People:** How can 3D printing benefit the people in low resource settings?
- 2. Profit:** How can 3D printing stimulate local economy and entrepreneurship?
- 3. Planet:** How can 3D printing help towards a more sustainable planet?

Next the general limitations of FDM 3D printing as a production technology are explored.



Figure 2: Triple bottom line framework [14]

### 2.1.2 Benefits

The benefits of 3D printing for healthcare in low resource settings are described in terms of how it benefits (1) people, (2) profit and (3) the planet.



#### 1. People

How can 3D printing benefit the people in low resource settings?

##### Distributed, decentralized manufacturing

Healthcare systems in low resource settings like Kenya usually heavily rely on importing medical equipment, due to unavailability of local manufacturers. However, badly functioning or non-existent supply chains lead to excessive transportation costs, and long lead times [3]. According to the World Bank [15, 16] importing goods into areas like Sub-Saharan Africa is on average ten times as expensive, and can take up to 25 times longer than importing goods into high income countries. This problem is also heavily felt by humanitarian aid organizations, who are forced to spend 60-80% of all aid money on logistics [17].

By stationing 3D printers in close proximity to where medical equipment is needed, a new type of distributed or decentralized manufacturing can emerge. A network of small decentralized mini-factories (read: 3D printers) can locally produce goods when and where they are needed. This greatly reduces the reliance on complex international supply chains, and therefore drastically reduces costs and lead times, and ultimately increases accessibility to medical equipment in low resource settings [3, 17].

##### Producing equipment tailored to local needs

There is a huge mismatch between medical equipment shipped to low resource settings, and what these settings actually require. Currently, much of this equipment was designed for use in countries with adequate resources and

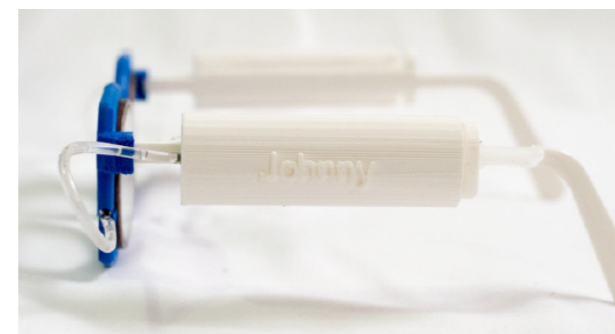


Figure 3: 3D printed self-adjustable glasses for low resource settings [3]

infrastructure, and therefore does not match the need in low resource settings of robust and affordable equipment [18]. Moreover, more customized equipment like custom fitted casts or prosthetics, usually require expensive materials, machinery and tools that is not available in low resource settings.



Figure 4: The Excelscope, a mostly 3D printed low cost malaria detection device

3D printing can be used to produce equipment tailored to local needs. For example, Gwamuri, et al. [3] developed 3D printable self-adjustable glasses for low resource settings, that are customizable to fit each individual's needs. These glasses can be produced for around \$6 and therefore also offer a significant cost reduction. Another notable example is a 3D printable stethoscope that can be produced for \$4, and performs similar to a conventional stethoscope costing around \$80 [8]. At the TU Delft, Cuellar, et al. [19] are developing a 3D printable pre-assembled prosthetic hand, that can be tailored to the individual with 3D scans made with a smartphone app. Other notable developments from the TU Delft are the ExcelScope [1] and the Schistoscope [2], which are low cost 3D printed devices that use a smartphone to respectively diagnose malaria and schistosomiasis.

##### Production of spare parts

In low resource settings 40% of medical equipment in hospitals is broken [20], of which 28% just requires spare parts to repair [21]. Unfortunately, these spare parts are rarely available, due to lack of standardization and the previously mentioned badly functioning supply chains [18].

With the help of free CAD design software, 3D printing can be used to produce spare parts locally and on demand. The Kijenzi team was able to fix a dozen \$1000 microscopes, they found sitting idle in a rural hospital in Kenya, with

3D printed adjustment knobs that cost a few cents to make [22]. Many similar examples were found where 3D printing had a huge impact through production of small and cheap spare parts [23].



#### 2. Profit

How can 3D printing stimulate economy and entrepreneurship?

##### Stimulating local economy

By producing 3D printers locally in e.g. Nairobi, the economy can benefit from an increase in job opportunities as well as local value creation. The distributed manufacturing model that was mentioned before, can also aid in stimulating the local economy, as it increases economic independence through local production of medical equipment instead of having to rely on imported equipment.

##### Promoting local entrepreneurship

3D printing can be used for production of a much wider range of products than just medical equipment. This opens up big opportunities for local entrepreneurship. According to Rogge, et al. [24] 3D printing can create opportunities for small businesses to enter markets producing and selling 3D printed products, with lower costs and fewer barriers to entry. Unlike traditional manufacturing methods like injection molding, 3D printing does not require any form of tooling, and therefore upfront investments are lower.



#### 3. Planet

How can 3D printing help towards a more sustainable planet?

##### Circular economy

According to Despeisse et al. "3D printing holds the potential to enable the shift towards a circular economy" [25]. By recycling used 3D printed products into filament, and using this for 3D printing purposes, a closed-loop material circulation system can be created. According to the Ellen MacArthur Foundation [26] a circular economy should also focus on retaining value of products through lifetime longevity. According to Sauerwein et al. [27] 3D printing can aid in this, as it can create opportunities to extend a products lifetime through repair or upgrades.

##### Recycling waste

Lastly, there's an exciting opportunity of turning plastic waste into usable filament. This opportunity is a perfect match for the distributed manufacturing model, as it enables the distributed manufacturing of the raw materials

needed for 3D printing [28]. The Digital Blacksmiths in Nairobi, have already started working on a recycling system that can produce filament from PET bottles [24]. Several other initiatives around the world are focusing on the same challenge, and it is just a matter of time before this will be possible [28, 29]. In a country like Kenya, there is an abundance of plastic waste and putting this to good use is a treasure waiting to be unlocked.

### 2.1.3 Limitations

It is clear that 3D printing can have a big impact in all three domains of the triple bottom line. However, the technology also has its drawbacks. General limitations of 3D printing as a production method are described next.

#### Material properties

Because of the process of layer-by-layer buildup, 3D printed parts exhibit anisotropic behavior. It is not uncommon for parts to show a 50% lower tensile strength along the Z axis, as opposed to the XY plane [30, 31]. Moreover, material properties of 3D printed parts are usually inferior to injection molded parts, since 3D printing results in a somewhat porous structure. As shown in table 1, 3D printed PLA shows average mechanical properties that are approximately 10% lower than that of injection molded PLA. It must be noted, however, that these values can vary greatly, as they can be influenced by parameters like material quality, printer calibration and sample orientation.

Mechanical properties	PLA Injection molded grade	PLA RepRap 3D printed
Tensile strength (MPa)	59	45
Elongation at break (%)	7	6
Elastic modulus (MPa)	3500	3368
UTS (MPa)	73	56.6

Table 1: Comparing material properties of PLA [30-34]. Note: The 3D printed parts were printed in the orientation that provides highest strength.

#### Reliability

Possibly the most important limitation is reliability. RepRap FDM printers are often fragile and unreliable [17]. They are known to require a lot of tinkering and maintenance in order to get the machine to function properly, and even then, the machines will need continuous maintenance to keep running correctly. This limited reliability has big

implications for the repeatability of the produced parts: A badly functioning printer will produce very inconsistent parts, which will have defects or deviations that are different for each print.

#### Poor surface quality

Since plastic is deposited layer-by-layer, 3D printed parts always exhibit a layered appearance, where individual layer lines are visible. Moreover, when printing large overhanging structures, usually support material needs to be added, which is difficult to remove afterwards, and always results in a poor surface quality. Lastly, the layered structure also makes the parts porous, making it very difficult to produce parts with water tight properties.

#### Slow production

3D printing is also known to be rather slow. Where an injection molding machine can make hundreds of parts per day, a 3D printer might be able to just produce a few parts per day. Printing a single part can easily take hours, depending on the size. Moreover, there is a lot of manual labor involved in removing parts when they're finished, and starting up a new print job.

## 2.1.4 Conclusion

### Benefits

In the domain of people, 3D printing can have big impact through a new type of distributed manufacturing, bringing the production of medical equipment directly to where it is needed. Moreover, it was found that 3D printing can produce equipment that is much more tailored to the needs of low resource settings, as it can produce much more affordable equipment, as well as equipment that is customizable to an individuals need. Lastly, it was found that 3D printing can be used to produce spare parts to fix the abundance of broken machinery often found in low resource hospitals.

In the profit domain, 3D printing was found to have a positive impact on the local economy through increased job opportunities and value creation, as well as local production of medical equipment. Moreover, it has been known to stimulate local entrepreneurship, since it enables entrepreneurs to setup their own 3D printing business.

In the planet domain, it was shown that 3D printing has the potential to enable a shift towards a circular economy, through the recycling and reuse of end-of-life 3D printed equipment. Moreover, an exciting opportunity was identified in the field of plastic waste recycling.

### Limitations

3D printing is known to have inferior material properties and a poorer surface quality as compared to injection molded plastics. RepRap 3D printers are known to be unreliable and fragile, which can be big problems for the context of low resource settings. Moreover, 3D printing can be a time consuming process, making it difficult to produce large batches of parts.

## Chapter 2.2

# Contextual analysis of Kenya

After giving a general overview of the benefits and limitations of 3D printing for healthcare in low resource settings, it is now important to dive deeper into the specific context of Kenya. The main goal of this chapter is to get a holistic overview of the context of Kenya, and to discover what implications this context has on the design of a 3D printer.

Through literature research, expert interviews and a field trip to Kenya, a list of insights will be gathered that have important implications on the design process. How this is exactly approached will be discussed next.

### 2.2.1 Method

To begin this analysis, several explorative interviews are conducted through Skype with local experts in Nairobi in order to get a first idea of the challenges involved with 3D printing in Kenya. Through literature research this starting point is broadened and validated to form preliminary findings. Finally, the field trip is aimed at further validating and broadening these findings through personal experience. In the end this leads to a complete and well validated list of insights that have direct implications on the design process. To see how this fits in the entire approach, please refer back to chapter 1.2 on page 16.

#### Expert interviews

To start off, several explorative semi-structured interviews were conducted with experts in Nairobi, Kenya. These interviews were held with:

- Derrick Mugasia [35], director of the MakerSpace, University of Nairobi
- Karl Heinz [36], co-founder of 3D printing startup AB3D

Also several explorative semi-structured interviews were conducted with connections from the TU Delft who are viewed as experts because they have made field trips to Kenya before. These involved:

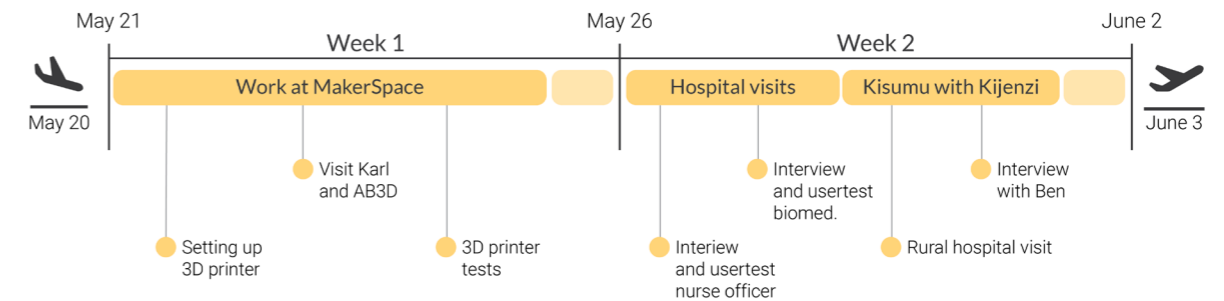
- Rutger van Rooden [37], master student at faculty 3mE, who had been on a three month internship to Eldoret, Kenya
- Julie Fleischer [38], researcher at faculty 3mE who had been on a field trip to Eldoret, and visited the MakerSpace in Nairobi, Kenya

Lastly, insightful email contact was conducted with:

- Roos Oosting [39], researcher at faculty 3mE who lived and worked in Nairobi for months
- Elizabeth Rogers [40], managing director of Nairobi based 3D printing webshop Kuunda 3D
- Daniel Kats [41], research engineer on the Kijenzi team

These interviews gave a first rough idea of the challenges involved with 3D printing in Kenya. The methods and results of these interviews and emails can be found in appendix F and G.

Figure 6: Schedule showing main activities during field trip



#### Literature research

The data gathered from the expert interviews was used as a starting point for a more in-depth literature research. A large amount of articles were consulted, varying between scientific publications, datasets and general websites, to strengthen and broaden the findings.

#### Field trip

The preliminary findings that resulted from the expert interviews and literature research form a solid scientific basis. However, to get a more qualitative view of the context, and to firsthand experience the implications this can have on 3D printing, a two week field trip to Kenya was conducted. To maximize learning, a first prototype 3D printer (based on a Prusa i3 MK3s) was taken to the field. This was used for simple tests, evaluating preliminary design solutions, and to spark interest, ideas and insights with interviewees. During this field trip the preliminary findings resulting from expert interviews and literature research could be validated and broadened, and many new insights were gathered.

The field trip took place from the 20th of May to the 3d of June. The bigger part of the trip was spent in Nairobi, and the last few days were spent in Kisumu, to meet up with the Kijenzi team. A basic schedule is shown in figure 6.

To validate preliminary findings and gather new insights, several research methods were used. These include technical testing of the prototype, semi-structured interviews with experts, hospital visits with user tests and interviews, as well as observation throughout the field trip. The semi-structured interviews were conducted with local

experts on sight:

- Karl Heinz [42], during a visit to his startup AB3D
- Ben Savonen [43], co-founder of Kijenzi

In the second week two visits were made to Kenyatta National Hospital. A semi-structured interview as well as two different user tests were performed with:

- Grace Wan'gombe [44], nurse officer of the Labor ward at KNH
- Edwins [45], administration management at KNH
- Regina [46], biomedical engineer at KNH

Lastly, many observations were made and recorded with a camera. These observations were made during visits to both the FabLab in Kisumu and MakerSpace of the University of Nairobi, as well as a privately owned FabLab in Kisumu. Also very insightful observations were made during visits to Nairobi based 3D printing startups Digital Blacksmiths and AB3D, as well as Kijenzi's lab in Kisumu. Lastly, the visits to Kenyatta National Hospital, and Nyakach County hospital, in a rural area close to Kisumu, provided a good perspective of different healthcare settings.

Setup, methods and raw results from the interviews and user tests can be found in appendices F and G.

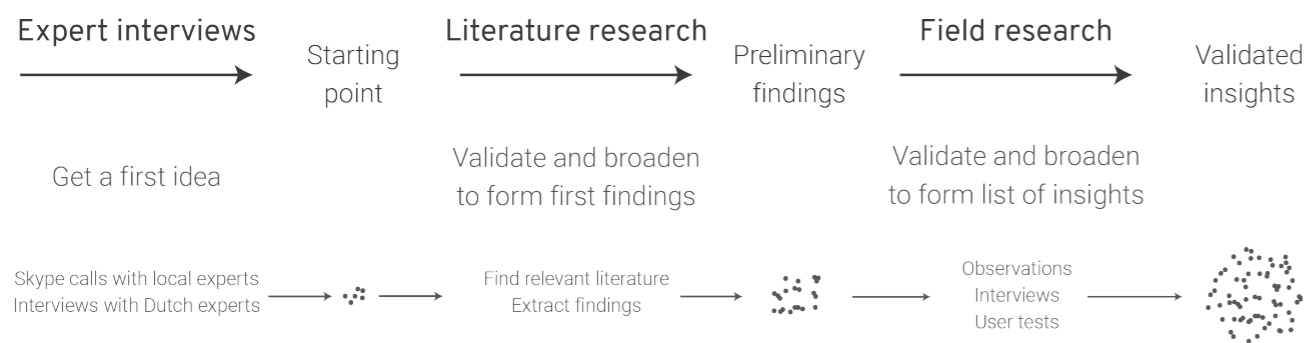


Figure 5: Visual representation of the approach for the contextual analysis

### Framework

To provide the reader with a complete and structured overview of all insights resulting from this context analysis, a framework was chosen to cluster and organize the insights. The Framework for Holistic Contextual Design for Low-Resource Settings by Aranda-Jan, et al. [47] was chosen as it fits this function perfectly. This framework helps to get an inclusive and structured picture of all aspects that are important when designing a 3D printer for healthcare in low resource settings like Kenya.

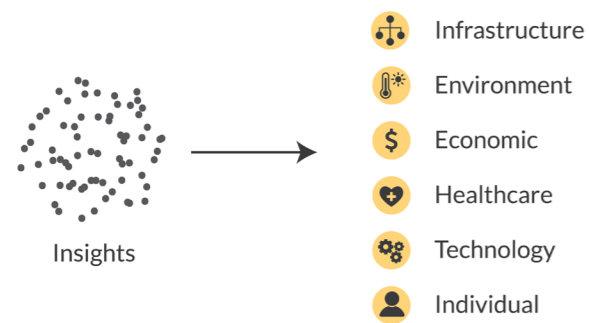


Figure 7: The insights are clustered into six domains

### Readability

When reading the next section, a reading aid is introduced to make it easier to distinguish which information was adapted from literature, and what was gathered through personal research.

The vertical yellow line indicates that this information has been found directly through expert-interviews, user tests and observations during or prior to the field trip.

Every domain is summarized by a list of insights, recognizable by this icon:

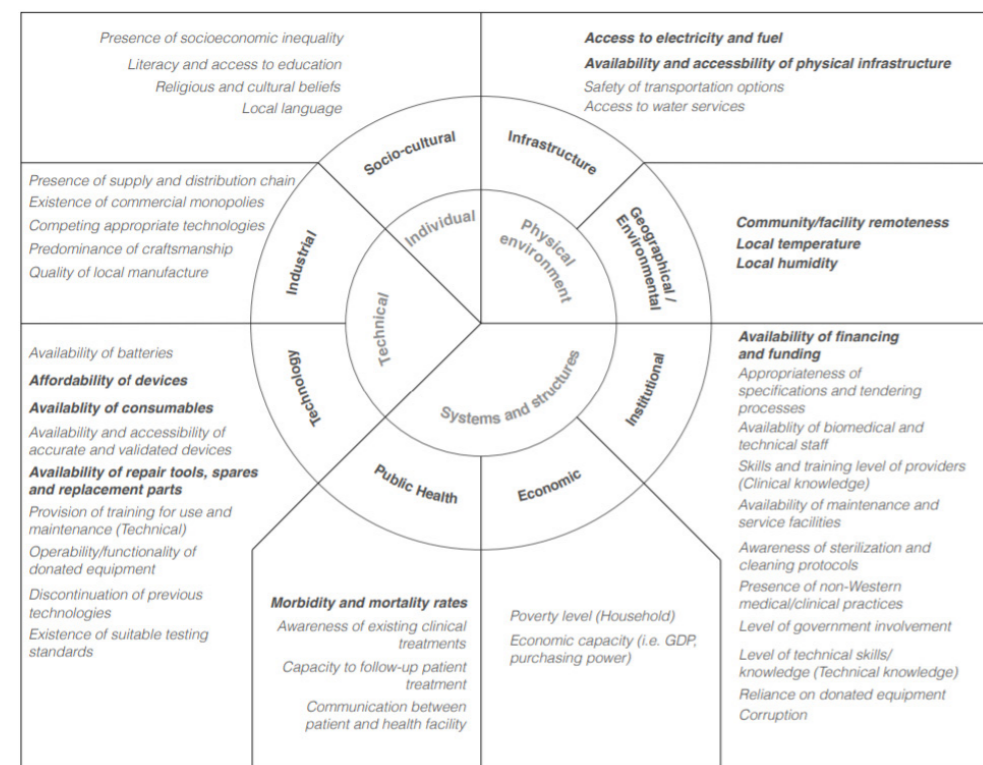


Figure 8: Framework for Holistic Contextual Design for Low-Resource Settings by Aranda-Jan, et al. [47]

*Note that not all of the domains and elements described in this framework are taken into consideration, as some are considered irrelevant or outside the scope of this analysis, such as the institutional domain. The technology and industrial domain have been merged together.*

## 2.2.2 Infrastructure

### Electricity

Electricity remains a shortage in almost all African countries. According to a study by Ramachandran et al. almost 600 million people living in sub-Saharan Africa lack access to electricity at home [48]. Moreover, even if areas have access to electricity, the power grid remains very unstable, with voltages varying between 100 and 300 Volts in urban areas like Nairobi, and 180 and 380 Volts in rural areas like Eldoret (Appendix B). Moreover, frequent power outages can be expected, sometimes several times a day. Kenya experiences an average of 6.7 power outages per month, which last approximately 5 hours per outage. During an explorative interview, Derrick [35] pointed out that the problem is not as bad in Nairobi, but further away from the city it becomes worse, and power outages become more frequent and take longer. Some universities and hospitals have backup generators however, that switch on after a few minutes and can provide power in case of an outage.

During the two week field trip to Kenya, the power went down 3 times. Usually this lasted only a few minutes, due to a backup generator taking over. This seems to be in line with the data found in literature. Residential areas in the city center of Nairobi usually have a backup generator, and this kicks in after a few seconds. The Kenyatta National Hospital also had backup generators in place, but they only provided power to essential departments of the hospital, the biomedical engineering department not being one of them.

### Digital infrastructure

According to Internet World Stats, as of 2018 Kenya holds a total of 43 million internet users, which is 85% of the country's population [49]. However, the World Bank Group states that 16% of Kenya's population uses the internet [50]. But since this data is from 2016, it is regarded less relevant.

From field research and explorative interviews it became clear that most hospitals do not have computers at their disposal, and most hospitals also don't offer WiFi. According to Roos [39], the national hospital in Eldoret owned one computer, which was stationed at the biomedical engineering department. Another big hospital in Mombasa equally possessed just a single computer. It must be noted that these are among the biggest hospitals

of the country. An exception to this might be the Kenyatta National Hospital (Kenya's largest hospital). During a visit to this hospital it became clear that there were no shortages of computers here. The labor ward alone had access to four computers, and also the biomedical engineering department owned a few computers. The hospital also had WiFi coverage, which all computers were connected to. However, it is safe to say that this is an exceptional situation, and that most hospitals, especially those in rural areas will not have computers nor WiFi.

According to Derrick Mugasia [35], people in these areas use cellular data to access the internet, using their smartphones. It was also observed during the field trip that many people in Kenya own a smartphone, and cellular network coverage is remarkably good. This is supported by literature [51, 52]. However, it was also observed that many Kenyans try to use their data sparsely, so usually only turn on 4G once or twice a day, or if it's really necessary.

In urban areas more people seem to own a computer or laptop. Especially under students it was observed that almost everyone owned at least one laptop.

### Physical infrastructure

According to a report by the World Bank, 54% of roads in Kenya are in good or fair condition, and 14% of all roads are paved [53]. According to the same report 37% percent of businesses identify bad roads as major business constraint.

From field research it became clear that the presence of roads in Kenya is quite good. Rural hospitals are usually



Figure 9: Roads at Nairobi University, picture taken during field trip

accessible by car. However, the condition of the roads encountered in both Nairobi and Kisumu were usually very bad. Densely populated areas will often have concrete roads, but once you get to more rural areas, you mostly encounter dirt roads. Potholes are numerous and treacherous, and drivers will usually try to avoid them by driving around them. However, this is not always possible and therefore the rides are usually very bumpy.

From a conversation with Ben [43] it became clear that the Kijenzi team had experienced many issues with transportation of printers. In one particular case, they had ordered a printer from a company in Nairobi, but were delivered with a non-functioning machine, that had been badly damaged during transport.

On the field trip to Kenya, I experienced the fragility of the printer during transport firsthand, as an important frame part was heavily bent during the flight. This could have been avoided with a hard suitcase though.

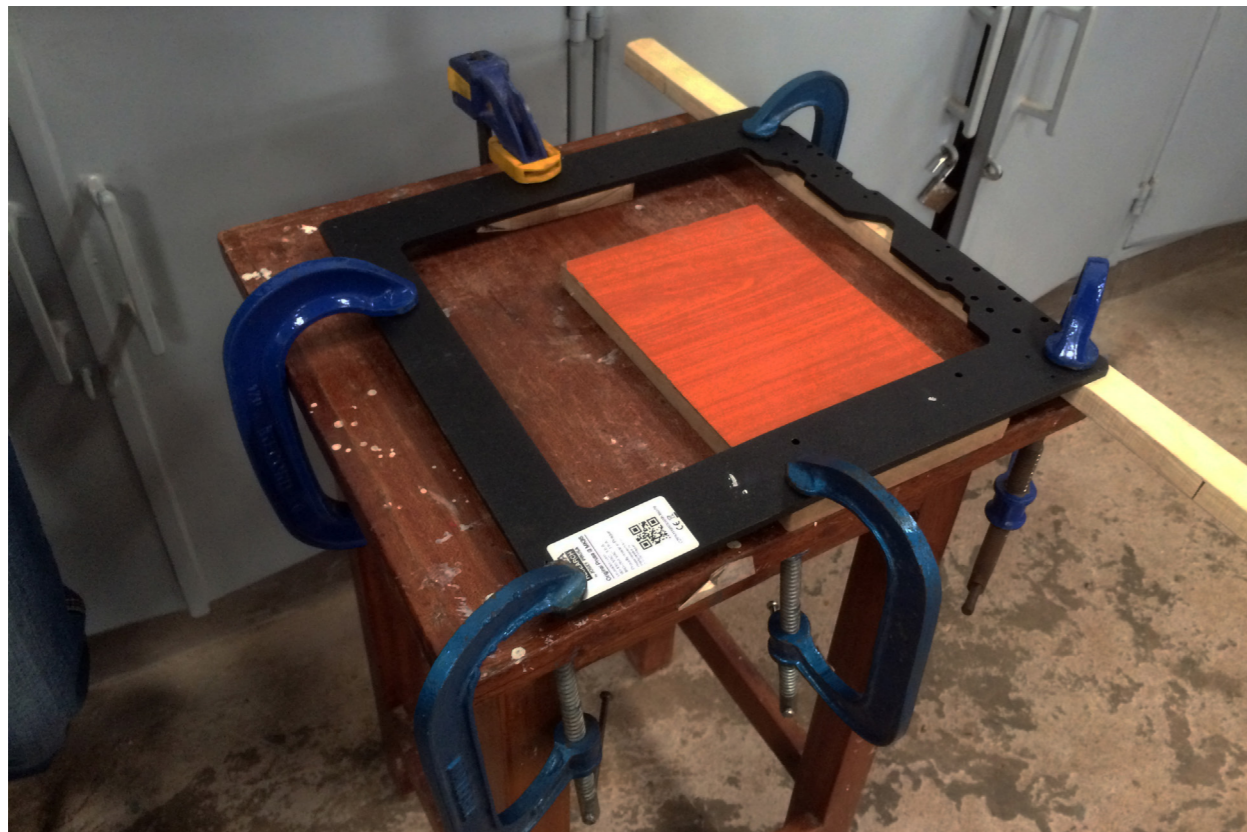


Figure 10: Trying to fix an important frame part that was heavily bent on the flight to Kenya

## Insights

- Kenya experiences frequent power outages, lasting several hours, especially in rural areas
- Hospitals and universities in urban areas are often able to rely on backup generators, which kick in a few minutes after a power outage occurs
- Power grid voltages can fluctuate heavily between 100 and 300 Volts, which is why many people use surge protectors
- Computers are rarely owned or used in rural Kenya
- Almost all Kenyan's own a smartphone, and cellular network coverage is remarkably good
- Bad roads can lead to rough handling of a 3D printer during transport
- During air transport suitcases are extremely roughly handled, which can easily lead to damaged parts

## 2.2.3 Environment

### Temperature

Low ambient temperatures can result in faster cooling and shrinking of layers, which can cause defects like warping. Great temperature fluctuations can also cause defects during printing, since different parts of the print will cool at different speeds. This can be a great source of printing inconsistency which should be avoided. In Nairobi, Kenya, the average maximum and minimum temperature is 24 and 11°C, and usually temperature fluctuations between day and night are around 8 °C [54]. From figure 11, it can be seen that Kisumu is on average 5 °C hotter.

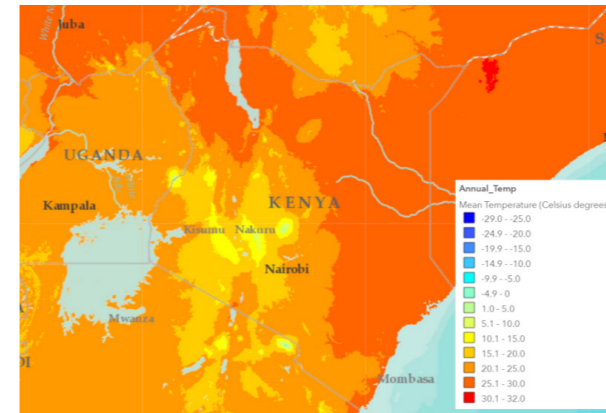


Figure 11: Mean annual temperature map of Kenya [55]

### Humidity

Humidity does not have a big influence on the printing process, but is known to influence plastics like PLA, ABS and PET. These materials absorb moisture from the air, and this can have a negative impact on print quality, and part yield strength [56]. In Nairobi, Kenya, humidity fluctuates between 60-70% [57]. This is approximately the same for Kisumu.

The Digital Blacksmiths tried to tackle this problem by developing a dehumidifier, that dries out moisture from filament with hot air, more about this in chapter 2.3.3 on page 36.

### Dust

According to several interviews explorative interviews, Kenya can be a very dusty country. Rutger van Rooden [37], a student who visited MOI hospital in Eldoret, stated that he had to weekly clean his laptop due to excessive dust accumulation. Accumulation of dust particles on e.g.

electronics, can cause overheating in due time. Moreover, an excess of dust can cause print defects, like warping because layers do not stick to the bed. Karl Heinz [42], CTO of AB3D indicated that they frequently experienced nozzle clogs due to dust accumulation in the nozzle. Ben Savonen [43], Founder of Kijenzi, indicated that they had to frequently clean and relubricate linear guides, due to dust accumulation.

A study on dust particles in Mali (West Africa) shows that 90% of all collected dust particles were bigger than 10 µm [58]. This is supported by a more recent study that assessed dust hazard in tanning facilities in Nairobi [59].

## Insights

- Humidity in Kenya is fairly high which has a negative impact on filament if left unprotected
- Some Kenyan 3D printer users store their filament in a dehumidifier box
- Kenya experiences excessive dust, which can cause many 3D printing problems, including nozzle clogs and poor bed adhesion
- High temperatures in Kenya are known to cause overheating problems with 3D printer electronics. This is aggravated by the presence of excessive dust
- Most dust particles in Kenya are 10 µm or bigger

## \$ 2.2.4 Economy

### General

According to the world bank Kenya's GDP grows rapidly and is currently at 80 billion USD [60], of which 5.7% is spent on healthcare [52]. The gross national income (GNI) per capita is currently at 1470 USD, which classifies the country as a Low-to-Middle-Income country (LMIC) [61]. Although it's clear that Kenya's economy is growing rapidly, employment is still shockingly low, with an unemployment ratio of 53% [62].

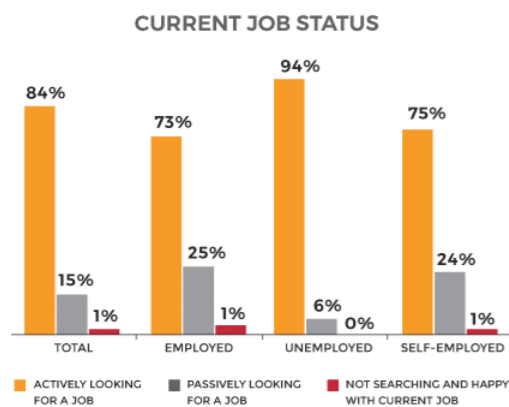
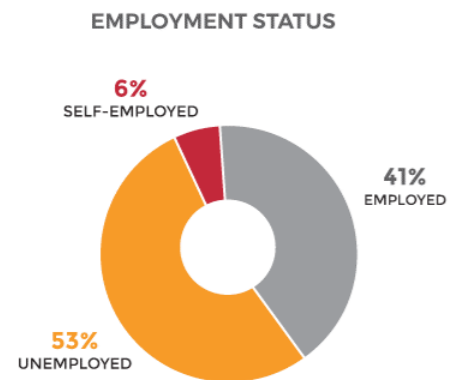


Figure 12: Current employment status in Kenya, reprinted from [62]

### Entrepreneurial “hustling” mindset

Observations and conversations during the field trip lead to the insight that many, especially young people in Nairobi are “hustling”, a popular term used to describe informal small businesses that people run to bring in an extra buck.

This can be the only source of income, but usually it is something that people run on the side to earn some extra cash. It illustrates perfectly how big the entrepreneurial mindset is in Kenya [63].

### Paying power for a 3D printer

Dan Kats [41] shared results from an (unpublished) study they performed to discover paying power of print shops in Kisumu, by interviewing print shops in the area. The shops usually had one large, office-grade printer and copy machine (\$1,200 - \$5,000). Cyber cafés and some print shops also invested in smaller home printers (\$100 - \$200). When asked about the large cost range of various machines, business owners unanimously answered that it is all dependent upon the machine's return on investment. One business owner indicated he'd like the cost of the machine to be paid off in the first two months. As this is a little ambitious, Kats and his team believe it is better to come up with alternative models, where the machine can be loaned or leased. Whatever the case, it is vital that the owner of a 3D printer can have as high an uptime as possible. For instance, printing day and night, instead of just during office hours, could easily double production output, and profits.

AB3D sells their 3D printers for \$400 to businesses, education institutes and hobbyists. Karl [42] (co-founder) estimated that the selling price of the envisioned printer should not exceed \$800.

### Insights

- Designing a product that can be produced locally can have an important impact on employment in Kenya
- Kenyan's have a big entrepreneurial drive, a good fundament for starting a 3D printing business
- Entrepreneurs are willing to pay between \$400 and \$800 for a 3D printer
- A business model where the machine is loaned or leased is probably most suitable for the context
- Business owners will want quick return of investment, a high uptime and productivity is essential

## + 2.2.5 Healthcare

### Shortages of medical equipment

To understand where shortages of medical equipment occur, one must first understand the Kenyan's healthcare system. The system is built on four different levels of care, distinguished by the level at which they operate, see figure 13.

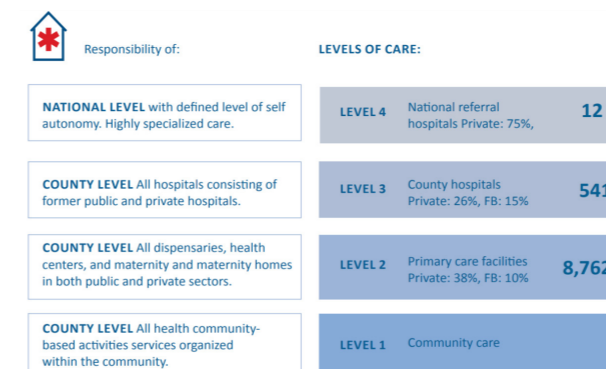


Figure 13: Kenyan's healthcare system, reprinted from PharmAccess [52]

According to a study by IHME, Kenyan health care facilities carried, on average, only 77% of the equipment that the World Health Organization lists as necessary [64]. For Kenyan dispensaries (usually the only option in rural settings), this number drops to 60%. Some dispensaries carry as little as 23% of the necessary medical equipment.

IHME's report on Kenyan health care facilities shows several lists of availability of functional medical equipment for different types of healthcare facilities. Adapted from these lists, and according to Kats et al. [22], currently the biggest impact can be made with items like:

- Basic medical equipment, like a surgical retractor [9] or stethoscope [8]
- Occupational therapy equipment, like a clubfoot brace [7]
- Medical equipment replacement parts, like aperture adjustment knobs [22]

### Materials in medical equipment

According to Ben [43], the Kijenzi team mostly printed tools and equipment with generic materials like ABS and PLA, but hospitals also sometimes request the use of flexible materials like TPU, as this allows them to offer a wider range of products, and is also often requested by the hospitals.



Figure 14: 3D printed medical equipment made by the Kijenzi team in Kisumu

### Dimensions of medical equipment

A quick study was made to determine dimensions of typical medical equipment suitable for 3D printing, added in appendix D. Most equipment fits within a 200x200mm area. The found dimensions are in accordance with a study aimed at designing and 3D printing medical equipment for space missions [65].

### Where to station a 3D printer

As mentioned earlier, healthcare facilities that are struggling most with hospital shortages are usually public and private dispensaries. National/provincial hospitals hold most of necessary equipment (> 95%) [64]. Therefore, the former healthcare sector should be the main target for producing medical equipment with a 3D printer.

During an interview at KNH, the biomedical engineer reacted quite offensive against the idea of having to operate yet another machine at the hospital. This attitude was also recognized by Ben, during a semi-structured interview [43]. The general consensus is that rural hospitals are too understaffed for stationing a 3D printer.

### Insights

- 3D printing can have the most impact for the rural healthcare sector, such as regional hospitals and dispensaries
- The healthcare sector requires 3D printed parts in generic materials like ABS and PLA, but also flexible materials like TPU
- Most printable medical equipment fits within a 200x200mm area, but some require a larger area
- It is not a viable option to place a 3D printer at a hospital, as they are too understaffed



## 2.2.5 Technology

### Access to 3D printer components

So far the development of 3D printing has mostly limited itself to the United States, Europe and a few Asian countries [66]. However, new initiatives are slowly rising in African countries, like Kenya. The Digital Blacksmiths and AB3D (both originated from the same company) [67], created a RepRap FDM 3D printer made from mostly locally sourced parts, such as e-waste stepper motors. The cost price of these recycled components can be found in Appendix E.

3D printer specialty parts, such as hotends, thermistors and controller boards, need to be shipped from overseas, which is typically done through AliExpress [68]. A report on average costs and shipping time can be found in appendix A. Usually shipping takes around 2 to 3 weeks. According to Karl [42] a rule of thumb can be used to estimate shipping and tax for goods ordered from AliExpress. On average these costs amount to \$10 per kg. It is also possible to order parts from Kenyan webshop Jumia [69]. Shipping is more affordable (usually around \$2.50), but goods are usually more expensive, and the selection is rather limited compared to AliExpress.

### Access to spare parts

Since several 3D printing companies have already started producing their own 3D printers in Nairobi, they can also serve as a local distributor of spare parts. However, in this case it is important to use generic components, like 12V components instead of 24V. During the field trip, the brought prototype was equipped with 24V parts, and when an essential part broke down, no spares could be found. According to Kuunda 3D, Nairobi based 3D printer and filament reseller, many of their clients hold their own stock of spare parts to avoid downtime [40].

### Availability of supply chains for filament

One spool of PLA filament can cost around \$ 40-50 (double the price of PLA filament in Europe), and delivery usually takes at least 2 weeks [40]. However, large amounts of waste PET are available, and there are initiatives of recycling this material into 3D printable filament [70]. It is very important that the 3D printer is able to print with this material, to anticipate for this future opportunity.

### FabLabs

Nairobi has two FabLabs, that where both visited during the field trip. These were equipped with 3D printers as well as machines like a lasercutter, CNC mill, lathe, and other more basic tools and machines. Kisumu also has a privately owned FabLab, with roughly the same facilities. Owners and employees of these facilities showed a great interest in the idea of stationing a 3D printer here for the production of medical equipment. The available tools and machines make it an ideal place for keeping the 3D printer up and running.

### Insights

- Access to 3D printer spare parts can be difficult. These parts often need to be shipped in from overseas, which can take weeks
- It is possible to locally source recycled stepper motors and fans for use in 3D printers
- 12V components are locally easier acquirable than 24V components
- Kenyan webshop Jumia is a good reference for finding accessible materials and components
- A great opportunity lies in the field of printing with local available material like PET, because it is available in abundance as waste plastic
- FabLabs are upcoming throughout Kenya, and are a good place to station and maintain 3D printers



Figure 15: The MakerSpace of the university of Nairobi. In the back you can see cupboards filled with eight 3D printers

## 2.2.6 Individual

### Step-by-step mindset

During a user test at Kenyatta National Hospital, one particularly interesting insight was that the biomedical engineer required a step-by-step instruction manual, because this is what she was used to. Later this was also confirmed by Ben [43], who hosted a two week course on operating a 3D printer. He noticed that the students similarly required step-by-step explanations. Another thing he noticed was that many Kenyan's had never used a computer before, and that it was a time-consuming process for them to get used to working with one. According to him, the step-by-step mindset is imprinted from childhood, as the Kenyan education system heavily focuses on this way of problem solving.

### Learning by doing

According to Rutger [37] and Julie [38], a generally accepting and curious view towards innovation is a mindset that can be observed in Kenya. Many people are very open to innovation, and show a deep interest in trying and learning new things, as well as experiment with emerging technologies. The same attitude was also experienced by the author during the field trip to Kenya, and was confirmed by another very interesting insight gathered during the user tests at KNH. All respondents would rather buy a partly assembled printer than a fully

assembled (and ready to use) printer. The main reason being that they want to learn and understand the printer through the assembly process. Ben [43] later confirmed that he recognized this mindset of learning by doing from his own experience with teaching locals.

### Insights

- Kenyan users will require a clear step-by-step instruction manual
- Kenyan users want to be able to assemble the 3D printer so they can understand how it works



Figure 16: Discussing product use with a biomedical engineer at Kenyatta National Hospital, Nairobi.

## Chapter 2.3

# State of the art analysis

Now that the context has been thoroughly analyzed, the next step is to explore current 3D printers and analyze why they are currently not suitable for use in low resource settings. This will be researched through a state of the art analysis looking at 3D printers designed for the western market, as well as 3D printers produced in Kenya, and lastly 3D printers designed for use in low resource settings. Important insights are extracted and summarized at the end of the chapter.

### 2.3.1 Method

To get a complete overview of the current state of the art of FDM 3D printers the scope will be temporarily broadened to also take into account non-RepRap printers. Data about printers is acquired through literature research as well as expert interviews and observations during the field trip. The current state of the art will be reviewed according to three different groups:

#### 1. 3D printers designed for the Western market

To begin, the western FDM 3D printer market is analyzed and segmented, and different popular machines from these segments are compared in a simplified infographic. The different machines are evaluated with regard to the context of Kenya.

#### 2. 3D printers designed and produced in Kenya

During the field trip, I came across several companies that locally produce 3D printers. These are the focus of this section, and will be analyzed with the goal of extracting insights for the design process.

#### 3. 3D printers designed for low resource settings

Lastly, earlier attempts of 3D printers designed for low resource settings will be visited. The success and failure stories will be analyzed and important insights that can be used in the design phase will be extracted.

Again, each of these sections will be concluded with a short list of insights.

### 2.3.3 3D printers designed for the Western market

Based on an extensive market research by Wohlers and 3DHubs, the current Western FDM 3D printing market can be divided into five different categories [71-73]:

1. Industrial: Big machines with highly controlled environment. Price range \$ 20.000 - 160.000
2. Prosumer: Relative high-end machines targeted at companies. Price range \$ 3.000 - 14.000
3. Workhorse: Machines designed to print nonstop with minimal failure. Price range \$ 750 - 2.500
4. Plug 'n play: Machines capable of printing directly out of the box. Price range: \$ 1000 - 2.000
5. Budget: Usually Asian branded machines designed for a low cost. Price range: \$ 200 - 1.000

#### Evaluation

The most typical printers from each segment were evaluated to understand how the segments differentiate from each other, as well as identify the suitability of the printers in the context of Kenya.

#### General

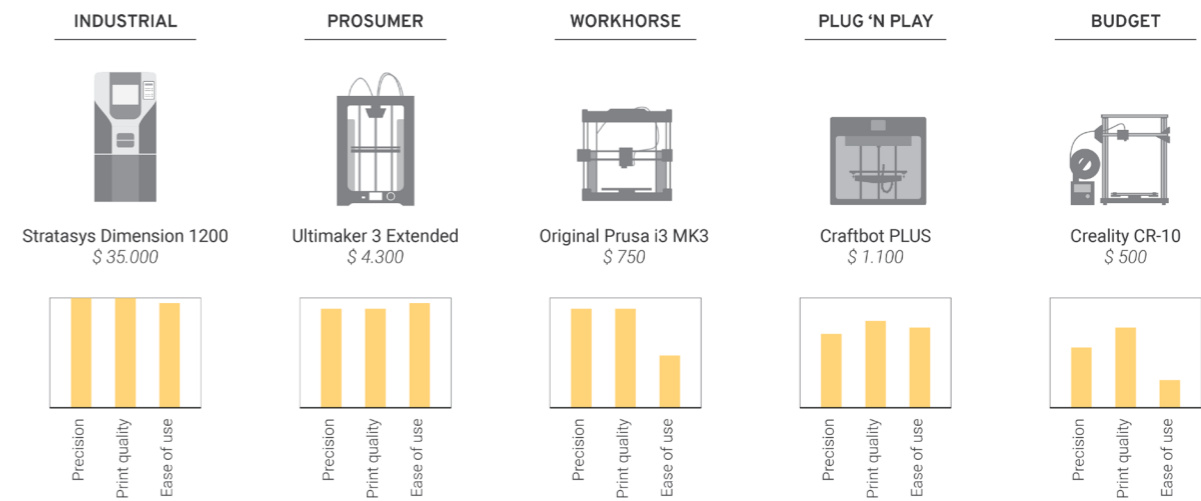
For this overview, the most typical printer out of each segment was chosen. They were all reviewed on three chosen criteria, based on data from 3DHubs [72]:

- Precision: The printer's ability to produce the same results over and over again.
- Print quality: A parameter that is influenced by factors like accuracy and surface quality.
- Ease of use: Taking into account how often the printer needs to be calibrated and maintained.

#### With regard to the context

The current printers were evaluated with regard to their suitability for the context, according to a preliminary set of requirements that followed from the context analysis. This is shown in table 2.

Figure 17: Comparison and evaluation of the most popular 3D printers in the current Western market



Requirement	Stratasys 1200	Ultimaker 3	Prusa i3 MK3S	Craftbot PLUS	Creality CR-10
Can produce high quality parts	Yes	Yes	Yes	Semi	Semi
Costs no more than \$800	No	No	Yes	No	Yes
Can deal with power outages	No	No	Semi	No	Semi
Can deal with excessive dust	Semi	No	No	No	No
Can be operated with a smartphone	No	No	No	No	No
Is easy to repair	No	No	Semi	No	No
Is made from mostly generic parts	No	No	Semi	No	Semi
Is able to print with generic materials	No	No	Yes	No	Semi
<b>Suitable for the context</b>	<b>No</b>	<b>No</b>	<b>No</b>	<b>No</b>	<b>No</b>

Table 2: Evaluation of the most popular 3D printer in the Western market in relation to the context of Kenya

### Conclusion

Looking at figure 17, and table 2, it is clear that currently 3D printers designed for the western market are not well suited for the context of Kenya. The printers are usually too expensive, and they are not able to deal with local challenges like frequent power outages or excessive dust. None of them can be operated with a smartphone, and they are usually difficult to repair. From table 2 it can also be concluded that what currently comes closest to a match for the context would be the Prusa i3 MK3S. This printer is known as a "Workhorse" because it usually produces repeatable good results, while being affordable. It is able to print with generic 1.75mm filaments, including TPU, and as a bonus, this printer also has a "power panic" function, that allows it to resume printing after a power outage has been resolved.



### Insights

- Current Western 3D printers are not well suited for low resource settings because they cannot be operated with a smartphone, are not affordable and cannot operate in harsh conditions
- The Prusa i3 MK3S is currently what comes closest to a match for 3D printing in low resource settings

### 2.3.3 3D printers designed and produced in Kenya

In Nairobi, there are several companies that build and sell their own 3D printers. During the field trip to Kenya, I came across the Digital Blacksmiths [67], AB3D [74] and QTron [75]. The first two companies built the same 3D printer, the last company has emerged last year and is building a higher end model. Many interesting insights were gathered from analyzing these printers.

#### Digital blacksmiths

The Digital Blacksmiths are a spin-off from AB3D, and they use a wall of homemade 3D printers to produce various items, such as a 3D printed microscope for educational purposes. They are also working on an extruder that can make filament from waste PET bottles. Because the PET absorbs a lot of moisture, they have developed a filament dehumidifier to dry out the filament.

#### Filament dehumidifier

The machine uses a heater with a fan to blow hot air in the enclosure. This is controlled through an Arduino together



Figure 18: Filament dehumidifier by the Digital Blacksmiths

with a temperature and humidity sensor. The entire setup costs around \$70 dollars, making it quite a pricy add-on.

#### AB3D

Nairobi startup AB3D builds and sells their own design FDM 3D printers. The printers are hand built in Nairobi with mostly locally sourced materials, like steel tubing and recycled electronics. The total production price lies around \$215, and they sell the printers for \$400.

#### Specifications

- Cartesian style frame
- Direct extruder for 1.75mm filament
- Supports PLA, ABS, PET, PETG and TPU
- Build envelope of 200x200x200mm
- Heated bed
- Manual bed levelling
- 220V AC, 12V DC
- Connectivity with SD card

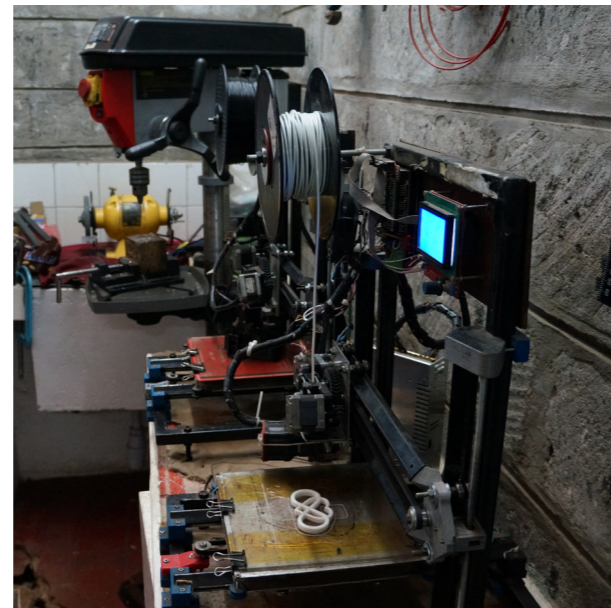


Figure 19: AB3D's 3D printers at their office in Nairobi

#### Common issues

In an interview with Karl [42], he shared what the most common issues are that clients run into when using these printers:

- Nozzle clogs, either due to clogging from dust entering the nozzle, or filament drag (can be fixed by mounting filament spool on bearings)
- Electronics failures due to overheating or misuse

- Laziness and unwillingness to do maintenance
- Levelling the bed can be too tedious or difficult for the user
- If many cables are visible on the outside, people will think it is not a finished product

#### QTron

QTron industries is a relatively new company that started producing printers in 2018. They distinguish themselves from AB3D by offering a higher end printer with a larger build volume. Although the printer looks more like a finished product compared to AB3D's printer, it still has many issues, as was experienced by the Kijenzi team in Kisumu.

#### Specifications

- Cartesian style frame
- Direct extruder for 1.75mm filament
- Supports PLA, ABS, PET, PETG and TPU
- Build envelope of 200x200x300mm
- Heated bed
- Automatic mesh bed levelling
- 220V AC, 12V DC
- Connectivity with SD card or app (Astroprint)

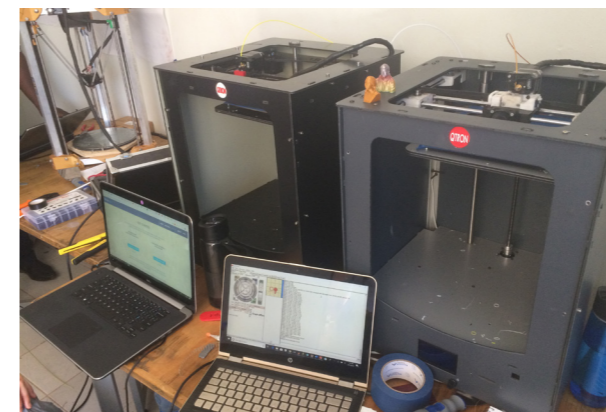


Figure 20: QTron printers at Kijenzi's lab

#### Common issues

The Kijenzi team was using two Qtron machines in Kisumu, and experienced the following issues:

- Electronics issues; they had to replace the controller boards with their own smoothieboards
- Bed levelling issues; automatic bed levelling procedure was not calibrated properly
- Nozzle clogs; aggravated by the use of cheap hotends



#### Insights

- Nozzle clogs are a frequent problem that can be caused by dust or filament drag
- Using cheap Chinese hotends can aggravate the frequency of nozzle clogs occurring
- Many users of AB3D find manual bed levelling tedious and difficult
- Using locally sourced recycled electronics is a viable option to reduce cost price of the printer
- A material dehumidifying solution is demonstrated by Digital Blacksmiths, but it is quite expensive
- Current 3D printers built in Nairobi use generic 12V components
- Cheap electronic boards (like RAMPS) are known to break down fast due to overheating

### 2.3.4 3D printers designed for low resource settings

Several initiatives have already tried developing a 3D printer specifically for the context of low resource settings, like Kenya. It is important to critically analyze these previous attempts, so findings can be used for the design process. One of the most notable initiatives was the development of the Kijenzi printer, by Savonen, et al. [10]. The group set out to develop a resilient 3D printer for humanitarian crisis response. Several other researchers were successful in developing a solar-powered 3D printing system for developing countries [76, 77].



Figure 21: The original Kijenzi printer, at Kijenzi's Lab, Kisumu

#### Kijenzi printer

The Kijenzi team set out to develop a resilient and transportable 3D printer specifically for the context of developing countries. A design was made with eight design elements in mind: FDM 3D printing, open source RepRap design, modular, separate frame, protected electronics, on-board computing, flexible power supply and climate control mechanisms.



Figure 22: Kijenzi's method for stopping dust included a simple dust filter [10]

The final result was produced for a cost price of \$ 520, and could be disassembled and fitted in a duffle bag, for easy transport. The climate control mechanism was realized in the form of dust filters and fans, to prevent dust from reaching the electronics, and to prevent the electronics from overheating. The printer was also able to deal with power fluctuations with the help of its power supply unit. However, it was not able to deal with power outages. Another drawback was the printers disability to be easily used. Unfortunately, it was quite cumbersome and complicated to calibrate the Kijenzi printer, as is usual with Delta type printers.

#### Solar powered 3D printers

Two cases were found that successfully developed a solar powered 3D printing system, for low resource countries. Gwamuri, et al. [76] developed a stand-alone battery charging system integrated to a MOST-delta RepRap 3D printer. The total cost was estimated at \$ 400 for the printer, and \$ 630 for the solar system. The most significant finding of the study is that it is indeed possible to power a 3D printer off-the grid with a simple solar power system, even when occasional clouds block the sunlight. The voltage alternated between 11.85 and 12.11 Volts, a variance of less than 2.5%. A study by King et al. [77] reported roughly the same results, and were similarly successful in off-the-grid 3D printing with solar power. They used a foldable RepRap 3D printer (FoldaRap), in combination with a few solar panels. The entire system can be fit in a suitcase, and is therefore easily transportable. The total cost of the system was \$ 1300, very similar to Gwamuri's results.



Figure 23: Power 3D printers from a solar power setup [76]

#### Insights

- Delta type printers are difficult to calibrate, unless it involves auto calibration features
- An enclosure with dust filter and fan are a good way to keep the electronics cool and dust free
- Kijenzi's eight fundamental design elements [10] are found to be beneficial, but also insufficient for the development of 3D printer fully ready for deployment in a country like Kenya
- Solar power and batteries are able to power a 3D printer off the grid
- A solar powered system increases costs substantially. It can cost around \$ 600

## Chapter 2.4

# List of all insights

This chapter provides an overview of the many insights that resulted from the analysis phase and have direct implications on the design.

### Background analysis

- 3D printing can enable a distributed manufacturing model
- 3D printing can be used to produce equipment tailored to local needs of low resource settings
- 3D printing can be used to produce spare parts
- Limitations of the technology include anisotropic material structure, poor surface quality, poor mechanical properties, low reliability and slow production

### Contextual analysis

#### Infrastructure

- Kenya experiences frequent power outages, lasting several hours, especially in rural areas
- Hospitals and universities in urban areas are often able to rely on backup generators, which kick in a few minutes after a power outage occurs
- Power grid voltages can fluctuate heavily between 100 and 300 Volts, which is why many people use surge protectors
- Computers are rarely owned or used in rural Kenya
- Almost all Kenyan's own a smartphone, and cellular network coverage is remarkably good
- Bad roads can lead to rough handling of a 3D printer during transport

#### Environment

- Humidity in Kenya is fairly high which has a negative impact on filament if left unprotected
- Some Kenyan 3D printer users store their filament in a dehumidifier box
- Kenya experiences excessive dust, which can cause many 3D printing problems, including nozzle clogs and poor bed adhesion
- High temperatures in Kenya are known to cause overheating problems with 3D printer electronics. This is aggravated by the presence of excessive dust
- Most dust particles in Kenya are 10  $\mu\text{m}$  or bigger

#### Economy

- Designing a product that can be produced locally can have an important impact on employment in Kenya
- Kenyan's have a big entrepreneurial drive, a good fundament for starting a 3D printing business
- Entrepreneurs are willing to pay between \$400 and \$800 for a 3D printer
- A business model where the machine is loaned or leased is probably most suitable for the context
- Business owners will want quick return of investment, a high uptime and productivity is essential

#### Healthcare

- 3D printing can have the most impact for the rural healthcare sector, such as regional hospitals and dispensaries
- The healthcare sector requires 3D printed parts in generic materials like ABS and PLA, but also flexible materials like TPU
- Most printable medical equipment fits within a 200x200mm area, but some require a larger area
- It is not a viable option to place the 3D printer at a hospital, as they are understaffed

#### Technology

- Access to 3D printer spare parts can be difficult. These parts often need to be shipped in from overseas, which can take weeks
- It is possible to locally source recycled stepper motors and fans for use in 3D printers
- 12V components are locally easier acquirable than 24V components
- Kenyan webshop Jumia is a good reference for finding accessible materials and components
- A great opportunity lies in the field of printing with local available material like PET, because it is available in abundance as waste plastic
- FabLabs are upcoming throughout Kenya, and are a good place to station and maintain 3D printers

#### Individual

- Kenyan users will require a clear step-by-step instruction manual
- Kenyan users want to be able to assemble the 3D printer so they can understand how it works

### State of the art analysis

#### 3D printers designed for the Western market

- Current Western 3D printers are not well suited for low resource settings because they cannot be operated with a smartphone, are not affordable and cannot operate in harsh conditions
- The Prusa i3 MK3S is currently what comes closest to a match for 3D printing in low resource settings

#### 3D printers designed and produced in Kenya

- Nozzle clogs are a frequent problem that can be caused by dust or filament drag
- Using cheap Chinese hotends can aggravate the frequency of nozzle clogs occurring
- Many users of AB3D find manual bed levelling tedious and difficult
- Using locally sourced recycled electronics is a viable option to reduce cost price of the printer
- A better solution needs to be found for dehumidifying materials
- Current 3D printers built in Nairobi use generic 12V components
- Cheap electronic boards (like RAMPS) are known to break down fast due to overheating

#### 3D printers designed for low resource settings

- Delta type printers are difficult to calibrate, unless it involves auto calibration features
- An enclosure with dust filter and fan are a good way to keep the electronics cool and dust free
- Kijenzi's eight fundamental design elements [10] are found to be beneficial, but also insufficient for the development of 3D printer fully ready for deployment in a country like Kenya
- Solar power and batteries are able to power a 3D printer off the grid
- A solar powered system increases costs substantially. It can cost around \$ 600



Edwins acting like the printer  
is super easy to carry  
KNH, Kenya

## Chapter 3

# Synthesis

All of the insights gathered during the analysis phase form a good basis for the design phase. However, the current format, a giant list of insights, is not very practical. Therefore, these insights will be converted into more workable formats that can be put into practice during the design phase.

## Chapter 3.1

# Method

The list of insights will be converted into three partical and workable formats. A list of design challenges, a list of requirements, and a set of design drivers

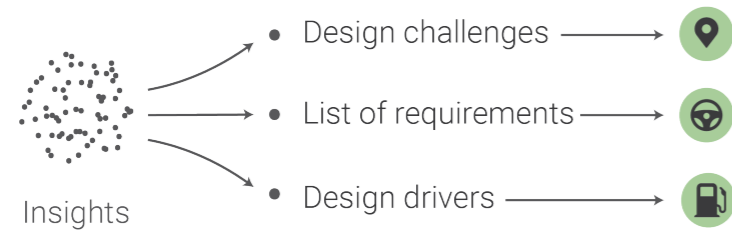
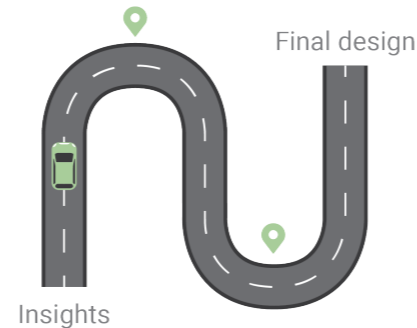


Figure 24: Visual illustrating the Synthesis approach



One can compare this design process with a car. Along its way, the car should drive by each of the design challenges. The list of requirements can be used to steer the car in the right way. And lastly, the design drivers are what fuels the car.

### Design challenges

This list of challenges will be formulated based on the most important challenges for 3D printing in low resource settings that were identified during the context analysis of Kenya.

### List of requirements

According to the method described in the Delft Design Guide [13], a comprehensive list of requirements will be setup based on the insights found in during the analysis.

### Design drivers

According to Kilian, A. [78]: “A design driver is a prominent constraint in design exploration that is not easily changed and provides the strongest influence for directing the exploration”. However, the word constraint is out of place here, as this relates more to the list of requirements. Therefore, this definition will be slightly changed to be more adapted to this project: “A design

driver is a prominent criterium that is not easily changed and provides the strongest influence for directing the exploration”.

To set up this list of design drivers, first a list of needs is identified. This will then be converted into a set of design drivers, that are primarily aimed for decision making and evaluation purposes during the design phase.

## Chapter 3.2

# Design challenges

During the analysis phase many challenges were found for 3D printing in a context like Kenya. The most important of those challenges have been defined as follows.

The found insights were used to identify a set of six design challenges. The analysis has shown that solutions need to be found for each and every one of these challenge areas.

The challenges have been listed in order of their priority.

**Power**  
The printer should be able to operate on an unstable grid

A very important insight from the context analysis was that the printer should be able to operate on an unstable power grid with frequent power outages, and surges. A solution needs to be found to tackle this challenge.

**Dust and heat**  
The printer should be resilient against dust and high temperatures

Another part of the embodiment process should be focused on finding solutions to tackle the problem of excessive dust. The electronics should be enclosed, and a dust filter on the extruder should stop dust from creating clogs. Lastly, a solution should be found for dust accumulating on the print bed.

**Continuous printing**  
The printer should be able to maintain a maximum uptime

The analysis also showed that it is important that the printer has a high uptime. A continuous printing system would allow the business owner to produce parts, even when he or she is sleeping.

**Connectivity and use**  
The printer should be useable by anyone, without a computer

Part of the context analysis showed that the printer should be operateable without the use of a computer. Currently almost all 3D printers need a computer to be setup. To take this element out of the equation, some research needs to be done and a solution has to be found.

**Transportability**  
The printer should be compactly transportable in a partly assembled state

Bad roads and rough handling can have disastrous effects on the printer during transport, as the Kijenzi team has had several first hand experiences with. Another important insight was that the user had a desire to receive the printer partly assembled so he or she can get a basic understanding of the machine during the assembling it.

Note that the first three challenges are considered most important, and will be the primary focus of the design phase. The last two challenges will be tackled on a more conceptual level.

## Chapter 3.3

# List of requirements

Many of the found insights could be converted into useful requirements for the design of a 3D printer for low resource settings.

These requirements were setup at the start of the design phase. A new list of requirements was developed at the end of the project, and can be found in appendix T.

Group	#	Req/Wish	Description
General	1.1	Req	The printer should be able to produce parts with a maximum tolerance of $\pm 0.5\text{mm}$
	1.2	Req	The printer should be able to print with a minimum layer height of 0.1mm
	1.3	Req	The printer should have a build envelope of 200x200x200 mm
Materials	2.1	Req	The printer should be able to print with 1.75mm filament
	2.2	Req	The printer should be able to print with at least: PLA, ABS, PET, PETG and TPU
	2.3	Wish	The printer should include a dehumidifying solution for the filament
Cost	3.1	Wish	The selling price of the printer should not exceed \$ 800
	3.2	Wish	The production price of the printer should not exceed \$ 400
Use	4.1	Req	The printer should be able to run and be setup with a smartphone
	4.3	Req	The printer should be easy to use by anyone with minimal instructions
	4.2	Req	The printer should be accompanied by a clear step-by-step instruction manual
Production	5.1	Wish	The printer should be made from, as much as possible, locally available parts and materials
Repairability	6.1	Req	Parts that need common maintenance or replacement should be easily reachable
	6.2	Req	The printer should be repairable with mostly generic and locally available parts
Dust prevention	7.1	Req	The extruder should include a dust filter to prevent dust from entering the nozzle
	7.2	Req	The printer should be able to blow off dust from the print bed prior to printing
	7.3	Req	The electronics should be protected from dust down to 10 $\mu\text{m}$ (IP5)
	7.4	Req	The electronics should be properly cooled to prevent overheating issues (max 70°C)
Power	8.1	Req	The printer should run on 12V
	8.2	Req	The printer should be able to operate on a grid fluctuating between 180 and 380 Volts
	8.3	Req	The printer should be able to run off-the-grid for at least 5 minutes during an outage
	8.4	Req	The printer should be able to resume printing after a longer outage has been resolved
Transportability	9.1	Req	The printer should be compactly transportable, without risk of damaging components
	9.2	Req	The printer should be delivered partly assembled
	9.3	Req	The printer should be easily transportable when it is fully assembled
	9.4	Req	The printer should be carryable by an average person (max weight 10kg)

Table 3: List of requirements

## Chapter 3.4

# Design drivers

In this chapter the most important needs that were identified during the analysis are converted into a set of three design drivers.

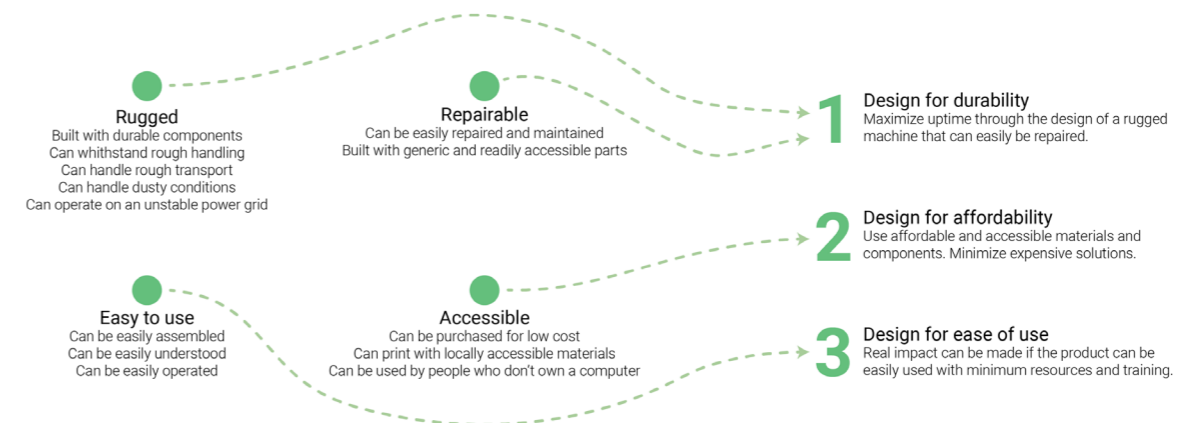


Figure 25: Showing the process of converting needs to design drivers

### 1. Design for durability

For the intended use case, it is very important that the printer has a high uptime. This means the printer should be built from durable parts, it should be designed to be withstand rough transport and handling, and should be able to handle dusty conditions and an unstable power grid. Over time 3D printers will always require maintenance and repair so it's important that the machine can be easily repaired.

### 2. Design for affordability

From the context analysis it became clear that cost price should be a driving factor for the design process. Kenya is a LIMC and business owners cannot afford very expensive machines. To make the printer accessible for the intended context, the cost price should therefore be minimized.

### 3. Design for ease of use

The intended use of production instead of prototyping requires a different workflow, and a different product-user interaction. In this new workflow, ease of use should be a core design driver. Moreover, the context analysis showed that there is currently very little knowledge about 3D printing in Kenya. Therefore it is vital that the printer is also easy to understand and maintain.





## Chapter 4

# Principal Design

Before diving into the core of the design phase, it is important to lay a solid foundation. To that end, this chapter will first frame the design space, by defining what the product will do, who will use it, and how and where it will be used. Next, several considerations are made that define the fundamentals of the 3D printer. This leads to the Prusa i3 MK3s. This printer will be used as a starting point for the embodiment phase.

## Chapter 4.1 Method

In this chapter the method is described that was used throughout the design process.

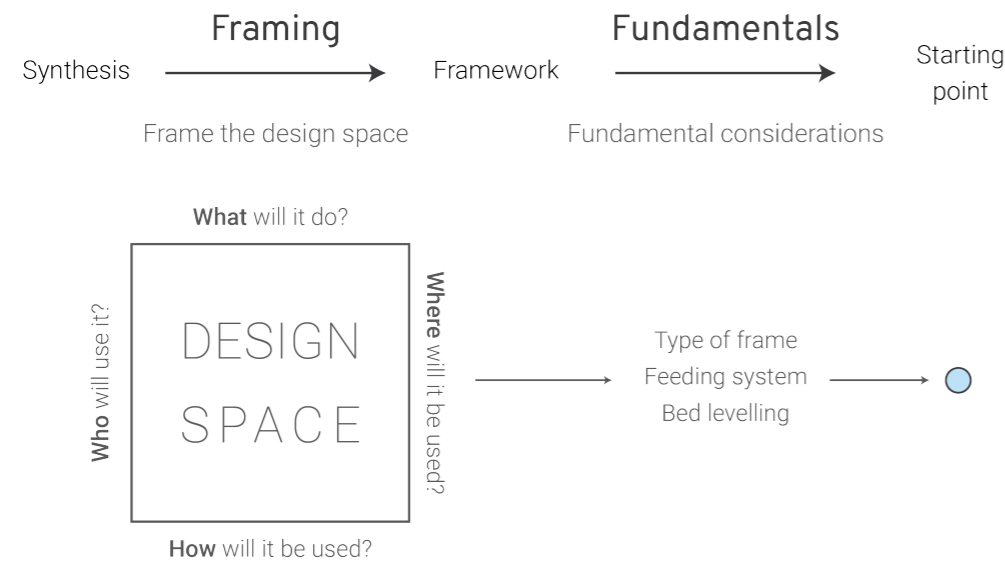


Figure 26: Visual representation of the approach used in this phase. The blue dot refers to the Prusa i3 MK3s, the starting point of the embodiment phase

The design phase is split up into three parts. First the design space needs to be framed. Next, some fundamental considerations are made that define the basics of the 3D printer. This will form the starting point of the embodiment phase: Diving into each of the design challenges to find solutions. This process is illustrated in figure 26.

### Framing

To bring focus into the design phase, it is important that the design space is properly defined. To define this framework, answers to the following question will need to be given:

1. What will the product do?
2. Where will the product be used?
3. Who will use the product?
4. How will the product be used?

### Fundamentals

When the framework has been properly defined, it is key to make some fundamental considerations before diving into the core of the design phase. These fundamental considerations are made in terms of what type of frame should be used, which feeding system to choose, and lastly

how the bed should be levelled.

The answers to these considerations will be used to choose a starting point for the core design phase. For this starting point, a 3D printer will be chosen that can be easily procured, matches the fundamental considerations and fits closest to the context.

## Chapter 4.2 Framing

In this chapter the design frame is defined by answering four fundamental questions.

To clearly define the frame of the design space, several definitions need to be made about product use.

*Note: this framework was updated throughout the design process due to new insights and findings.*

### What will the product do?

The 3D printer will be primarily used for the production of medical equipment for hospitals. The analysis showed that the 3D printer will be best suited for printing:

- Low volume single use items like tweezers, stethoscope or surgical retractors
- Medical equipment replacement parts, like a microscope adjustment knob
- Other equipment like occupational therapy tools or anatomy models.

A full list of 3D printable items requested by rural hospitals in Kisumu was put together by Kats, et al. [22].

### Where will the product be used?

The printers will be stationed at venues like a print shop or FabLab.

### Who will use the product?

The printer will be used by a printer operator. This can either be the business owner of the shop, or an employee. They will need to be educated to learn how to operate the printer.

### How will the product be used?

Currently envisioned product use is as follows: Whenever inventory management finds that the hospital is in need of new or replacement parts, they will open up an app on their smartphone in which they can select the items they need. This order request will then end up at the nearest business owner who is able to print the parts. He, or his employee, can accept the order, and send the task to the printer.



Figure 27: The office of AB3D is a good example of how a 3D printing venue could look like, where they would be stationed in Kenya

## Chapter 4.3

# Fundamental considerations

*In this chapter several fundamental considerations are made that will have a big impact on the rest of the design.*

Before diving into the core of the design phase, some important decisions need to be made concerning the fundamentals of the printer. Considerations need to be made concerning the type of frame, the extrusion system and how the bed is levelled. All of these fields have a huge influence on the functioning of the final printer. Decisions will be made based on research and design drivers.

### 1. Frame type

Arguably the most fundamental element of a 3D printer is its frame. A consideration needs to be made between a Cartesian, Delta, Polar or SCARA type frame.

### 2. Extrusion system

How filament is extruded has big implications for the functioning of a 3D printer. A choice needs to be made between a direct extrusion system or a Bowden system

### 3. Bed levelling

A level bed is crucial for high quality and consistent 3D printing. A consideration needs to be made between an extremely stiff frame, manual levelling or automatic levelling.

## 4.3.1 Frame type

FDM 3D printers come in four different types: Cartesian, Delta, Polar and SCARA. The last two categories are rarely used, and will only be considered for completeness sake. The most important consideration to be made is whether to use a Cartesian or Delta style frame. One particular study was found that compared results from both techniques [79]. They found that the Delta type printer produced parts faster, and with a better surface quality, while the Cartesian printer provided a better dimensional accuracy. However, this could be due to improper calibration of the Delta type printer. Also, this study only compared two printer models, and therefore the results are not regarded as strong evidence. The Kijenzi team chose for a delta frame, but later on regretted this due to the tedious calibration process that was required.

### Conclusion

Both SCARA and Polar solutions can quickly be discarded, as these are not well established, and rarely used, they will most likely introduce a lot of extra challenges, without having any clear benefit over Cartesian or Delta. Choosing between Cartesian and Delta is difficult however. Literature research shows many contradicting findings [79, 80].

The delta type printer requires higher computing, which would require a better (and more expensive) controller, e.g. a Raspberry Pi. Thus, choosing for a Delta type frame could increase the cost, and this is in conflict with the second design driver; design for affordability. Since ease of use is another design driver, the tedious calibration process that is required for setting up a delta printer is considered another major drawback.

**Cartesian style frame is considered most suitable.**


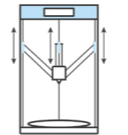
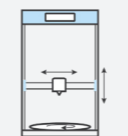
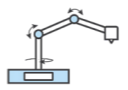
Type	✓ Pros	✗ Cons
 Cartesian	<ul style="list-style-type: none"> <li>Requires low computing power</li> <li>Popular and well established</li> <li>Rigid frame</li> </ul>	<ul style="list-style-type: none"> <li>Relatively slow</li> <li>Lower surface quality</li> </ul>
 Delta	<ul style="list-style-type: none"> <li>Higher speed</li> <li>Better surface quality</li> <li>Allows for a more modular design</li> </ul>	<ul style="list-style-type: none"> <li>Requires a lot of computing power</li> <li>Not as well established as cartesian type printers</li> <li>Usually low torsional stiffness in the frame</li> <li>Tedious calibration process</li> </ul>
 Polar	<ul style="list-style-type: none"> <li>Possibility of using just two motors</li> </ul>	<ul style="list-style-type: none"> <li>Not well established</li> <li>Poorly rated in the market [72]</li> </ul>
 Scara	<ul style="list-style-type: none"> <li>Requires less frame material</li> <li>More mobile design</li> </ul>	<ul style="list-style-type: none"> <li>Low stiffness and stability</li> <li>Not well established</li> <li>High cost</li> <li>Low quality</li> </ul>

Table 4: Fundamental consideration between different frame types: Cartesian, delta, polar or scara

### 4.3.2 Extrusion system

There are different ways to push, or feed the filament to the extruder. Commonly either a Direct feeder, or a Bowden feeder is used. For this comparison several online sources were used [80-82].

#### Direct feeder

This type of feeder is mounted directly on the carriage, and therefore sits very close to the extruder. This feeder is mainly seen in cartesian style printers, as the a direct feed printhead is too heavy for a delta type printer. The close proximity of the feed system to the extruder has several advantages, as a higher control can be gained over the filament. However, the added weight of the feeder on the carriage also causes several drawbacks.

#### Bowden feeder

The Bowden feeder is mounted stationary on the frame and feeds the filament to the extruder through a PTFE Bowden tube, hence the name. This way the printhead is a lot lighter, and can therefore move faster without causing problems like backlash. For this reason, delta type printers use this feeding system. However, the extended distance between the feeder and extruder has some drawbacks, as it can lead to delays in filament control.

#### Conclusion

Although the Bowden feeder allows somewhat faster printer, it does not work well with printing flexible materials, and this is a no-go. From the analysis an important requirement was found that the printer should be able to produce parts with flexible materials like TPU, and therefore:

**The direct extrusion system is required.**


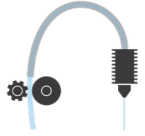
Type	✓ Pros	✗ Cons
 Direct	<ul style="list-style-type: none"> <li>Better retraction and overall control over filament feeding</li> <li>Good for flexible materials</li> <li>Works with lower torque motor</li> </ul>	<ul style="list-style-type: none"> <li>Heavier carriage</li> <li>Slower movement</li> <li>Higher risk of backlash, overshoot and frame wobble</li> <li>Takes up a lot of space on carriage</li> </ul>
 Bowden	<ul style="list-style-type: none"> <li>Lighter carriage</li> <li>Faster movement</li> <li>Higher precision</li> <li>Higher accuracy</li> <li>Compact</li> </ul>	<ul style="list-style-type: none"> <li>Does not work well with flexible materials</li> <li>Slower retraction can lead to oozing and stringing</li> <li>Requires higher torque motor</li> <li>Risk of getting clogs in the Bowden tube</li> </ul>

Table 5: Fundamental consideration between a direct or a Bowden extrusion system

### 4.3.3 Bed levelling

According to the RepRap community [83], several scientific articles [84, 85], and the authors personal experience, a level bed is crucial for a successful and accurate print. According to SD3D, the most frequent failure modes are Z-height error, bed-adhesion problems and an unlevel bed [86]. All of these problems can be improved with a proper bed levelling solution.

#### Manual levelling

Bed levelling is commonly performed manually by adjusting screws under the corners of the print bed. This is seen in almost all print segments, except industrial printers.

#### Automatic bed levelling

The latest trend in 3D printing is “Auto bed levelling”. The extruder gantry is fitted with a bed probing sensor. Prior to a print job a bed levelling sequence is performed by measuring the distance between the sensor and the bed on different location of the bed. This data is then used to correct the bed tilt by dynamically changing the Z height, within a layer.

#### Stiff frame

Another solution is to design and manufacture an extremely stiff frame with high precision components, like the Dutchy 3D printer [87]. This printer does not require any form of bed levelling, because the company guarantees perfect squareness and flatness.

#### Conclusion

The stiff frame solution fits perfectly with the first design driver “Design for reliability”. However, it is in conflict with “design for affordability”, as this will require precision machined parts. Besides this will also make it much more difficult to produce the printer in Kenya.

Manual levelling can be a tedious process that involves both getting the bed level, and getting the distance between the nozzle and bed just right. This process is made much easier with the automatic levelling procedure. One of the design drivers is to design for ease of use, and therefore:

**Automatic levelling is the solution of choice.**

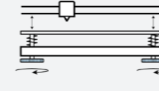
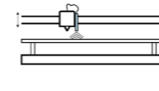
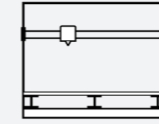
Type	✓ Pros	✗ Cons
 Manual	<ul style="list-style-type: none"> <li>Simple</li> <li>Cheap</li> <li>Effective</li> </ul>	<ul style="list-style-type: none"> <li>Difficult procedure</li> <li>Time consuming procedure</li> <li>Needs to be repeated frequently</li> </ul>
 Automatic	<ul style="list-style-type: none"> <li>Requires no manual labor</li> <li>Better results than achievable with manual levelling</li> <li>Can correct manufacturing mistakes</li> </ul>	<ul style="list-style-type: none"> <li>Slight increase in cost</li> <li>Requires very accurate Z positioning</li> </ul>
 Stiff frame	<ul style="list-style-type: none"> <li>Very effective</li> <li>Requires no labor</li> <li>Very reliable</li> </ul>	<ul style="list-style-type: none"> <li>Expensive</li> <li>Requires precision machined steel parts</li> </ul>

Table 6: Fundamental consideration on how the bed should be levelled, using manual or automatic levelling, or choosing for a stiff frame.

# Chapter 4.4

## Starting point

In this chapter a strategy for the embodiment phase is chosen. The Prusa i3 MK3s will be used as a starting point. This printer will also be briefly analysed to identify its strong points and weaknesses.

The first considerations led to the design of the following fundamental 3D printer:

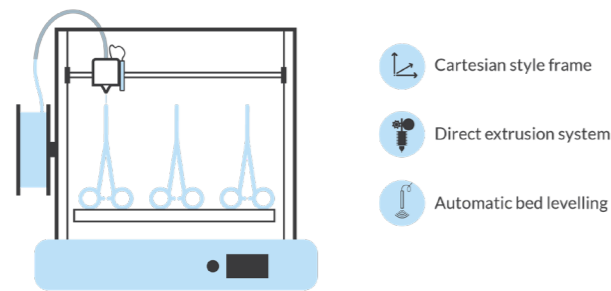


Figure 28: Theoretical fundamental design of a 3D printer for Kenya

### Strategy

The envisioned concept can be embodied in two ways:

- 1. Start with an existing 3D printer**  
This strategy requires less work, and there is a lower risk involved because the starting point is already a solid and functional foundation. The downside is that this will limit the design space.
- 2. Design a 3D printer from scratch**  
This strategy allows for much more design freedom, and might lead to more innovative solutions. However, there is a much higher risk involved, and taking this path will require a considerable amount of extra time.

The first strategy is the most time efficient, and involves lower risks. Therefore this is the strategy of choice.

### Choosing a starting point

From the state of the art analysis it followed that the current closest match for the context is the Prusa i3 MK3s. Moreover, the Prusa features a cartesian style frame with a direct extrusion system and automatic bed levelling. It already meets the fundamental considerations and is therefore perfect starting point for this project. Attention needs to be given to availability in Kenya of the components and materials that comprise this printer.

### Analyzing the Prusa i3 MK3S

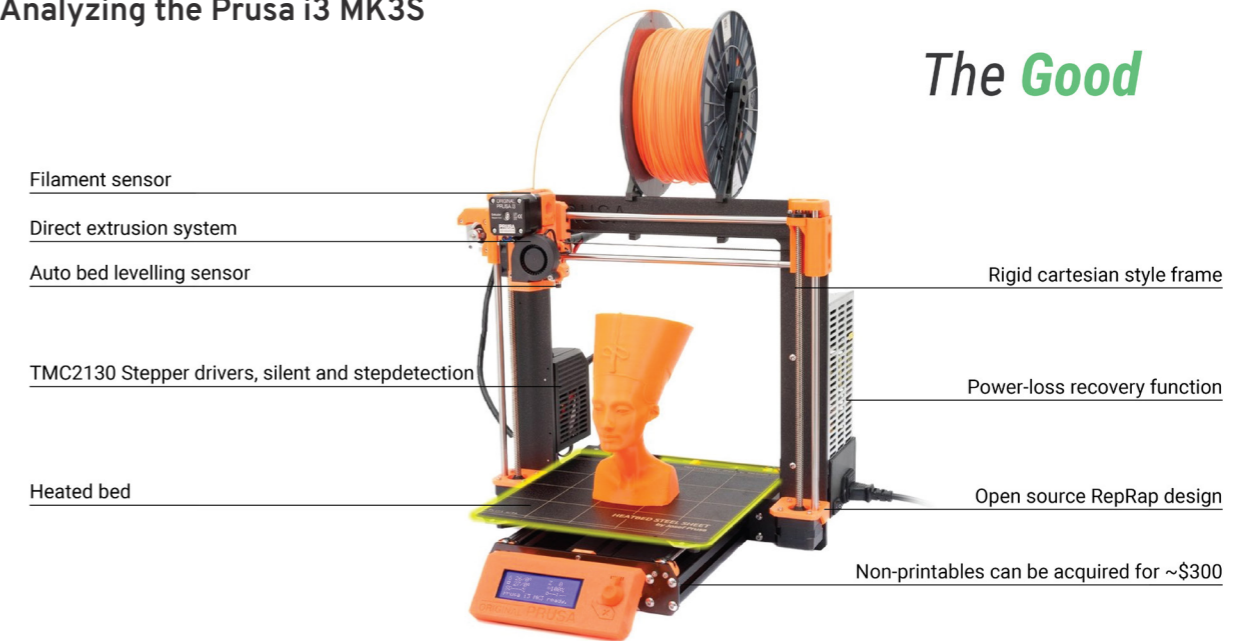


Figure 29: Indicating the Prusa's strong points

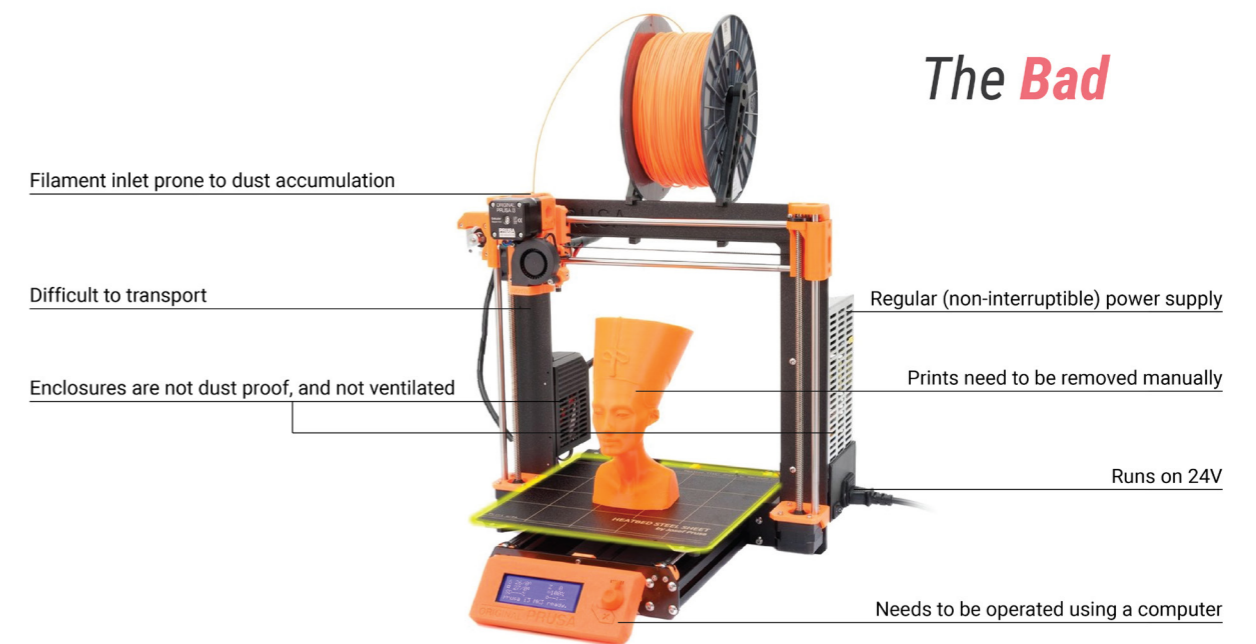
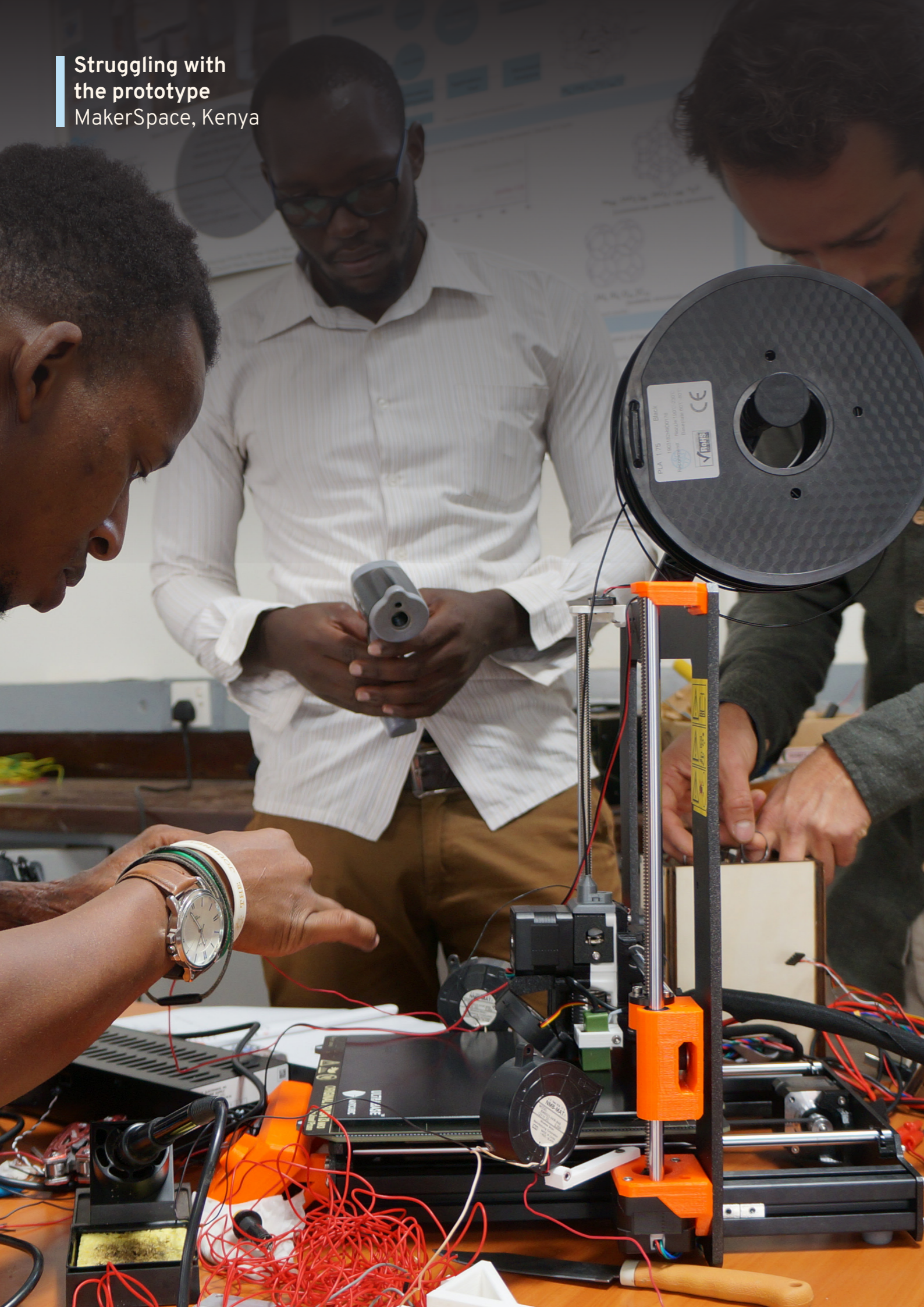


Figure 30: Showing the shortcomings of the Prusa



## Chapter 5

# Embodiment Design

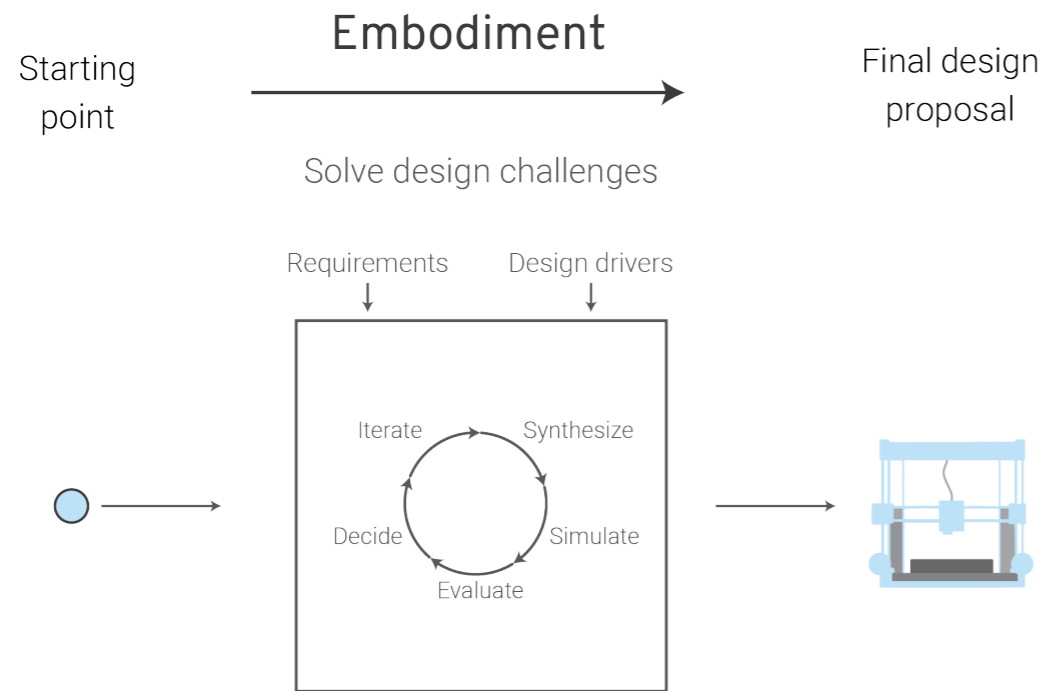
Now that a solid fundament has been layed down, it is time to dive into the core of the design phase, the embodiment. In this phase the design challenges identified in Chapter 3, Synthesis, will be tackled one by one, through rapid prototyping and testing. The last two challenges will be tackled only on a conceptual level.

Prepare for a massive amount of information, pictures and data.

## Chapter 5.1 Method

The method for the embodiment design phase will be briefly described and illustrated.

Figure 31: Visual representation of the approach used during the embodiment phase. For every design challenge a classic design cycle will be followed.



The embodiment forms the core of the design phase. In this section each of the challenges will be addressed and solutions will be sought through the basic design cycle as described in the Delft Design Guide [13]. The list of requirements and design drivers that resulted from the synthesis phase will be used to steer and drive the design process for every challenge.

### Prioritizing

Although each and every challenge is very important, there is not enough time in this project to develop high level solutions for every one of them. Therefore, some prioritizing needs to be done.

### Technological development

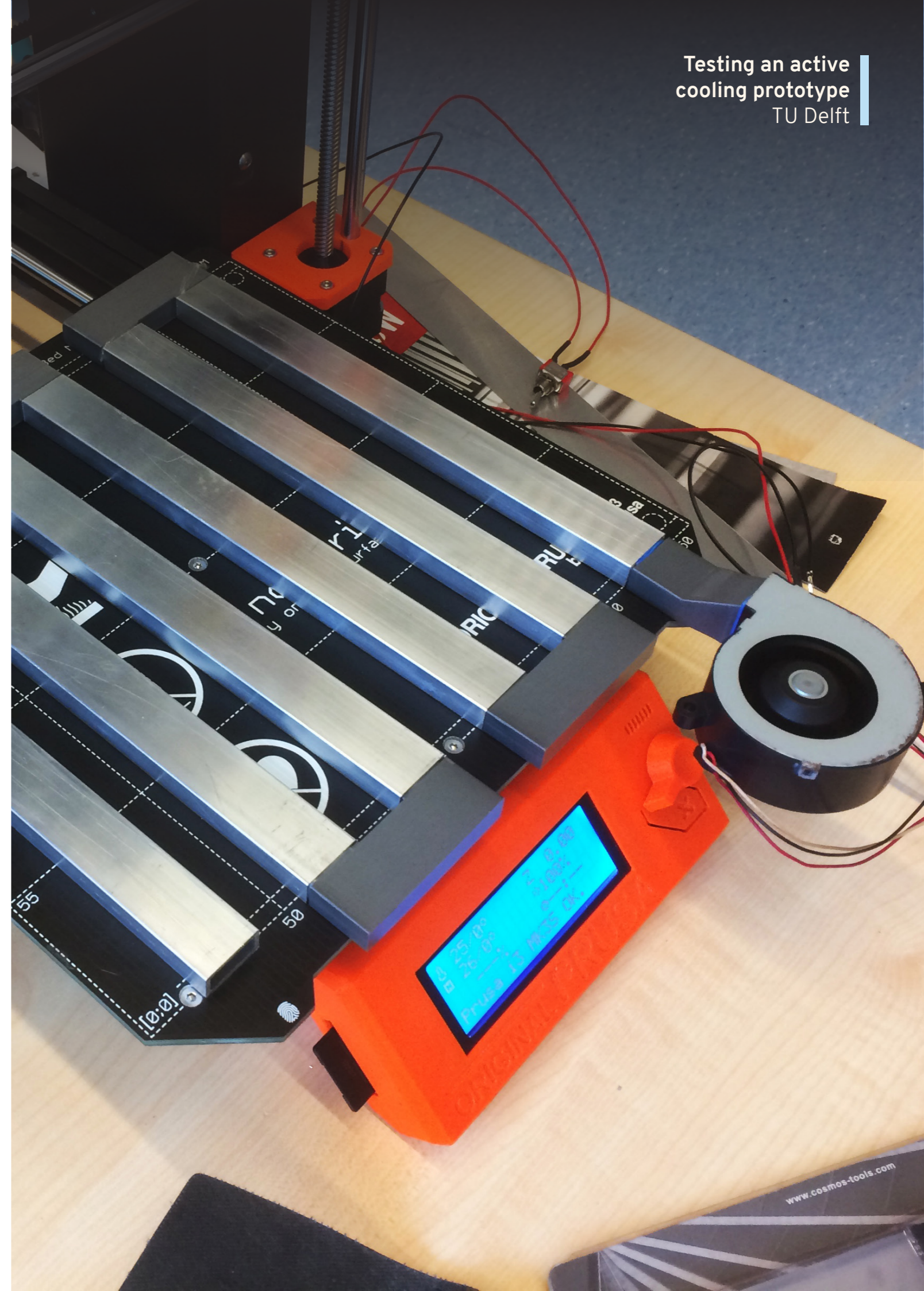
The following challenges will be the main focus of this phase. Tangible and feasible solutions will be developed through rapid prototyping.

1. Power
2. Dust and heat
3. Continuous printing

### Conceptual development

These last two challenges will be developed on a more conceptual level:

4. Connectivity and use
5. Transportability



## Chapter 5.2

# ⚡ Power

The printer should be able to operate on an unstable grid with frequent power outages

In this chapter several ideas are investigated, different concepts will be tested, and in the end a final solution will be developed.

### Main requirements

- The printer should be able to operate on a grid fluctuating between 180 and 380 Volts
- The printer should be able to run off-the-grid for at least 5 minutes during an outage
- The printer should be able to resume printing after a longer outage has been resolved

### 5.2.1 First ideation

To deal with the frequent power outages and surges that Kenya experiences, there are several solutions already available that can tackle this problem to some extent. A consideration needs to be made to define the correct approach for this challenge.





Type	✓ Pros	✗ Cons
 Surge protector	<ul style="list-style-type: none"> <li>• Protects against power surges</li> <li>• Cheap (\$ 7)</li> <li>• Plug 'n play solution</li> </ul>	<ul style="list-style-type: none"> <li>• Just cuts power in case of power surge</li> <li>• Has no effect on power outages</li> </ul>
 UPS	<ul style="list-style-type: none"> <li>• Protects against power surges</li> <li>• Continues power supply in a power outage, or surge</li> <li>• Plug 'n play solution</li> </ul>	<ul style="list-style-type: none"> <li>• Expensive (\$ 95)</li> </ul>
 Power-loss recovery	<ul style="list-style-type: none"> <li>• Allows for print recovery after power outage</li> <li>• Software solution</li> <li>• Requires no hardware</li> <li>• Very easy to implement</li> </ul>	<ul style="list-style-type: none"> <li>• Only allows for print recovery</li> </ul>
 Solar power	<ul style="list-style-type: none"> <li>• Makes the system operate independently of grid</li> </ul>	<ul style="list-style-type: none"> <li>• Very expensive (\$ 600)</li> <li>• Not well established</li> <li>• Not plug 'n play</li> <li>• Brings new risks and challenges</li> </ul>

Table 7: Consideration between different solutions to deal with the frequent power outages and surges in Kenya

#### Surge protector

A device commonly used in Kenya that plugs in between a power source and the device that needs to be protected. It cuts off the power once the voltage rises above a certain threshold.

#### Uninterruptible Power Supply (UPS)

This solution was found at KNH, to power computers in case of a power outage. A UPS contains a backup battery that will take over power in case of an outage

#### Power-loss recovery

This is a 3D printer software solution that allows the printer to continue printing where it left off, once the power has returned.

#### Solar power

Lastly, as shown in analysis chapter 2.3.4, page 38, it is possible to power a 3D printer from solar power, using a setup with solar panels and batteries.

### Conclusion

Solar power can be disregarded, as this will greatly increase the cost price of the system, and brings many new risks and challenges into the project, as it is not well established. A surge protector alone will not be sufficient, as it just shuts off all power in case of a power surge. Marlin's power-loss recovery function is very interesting, as it is a purely software based solution, and therefore does not have cost or other implications. This feature will therefore be included regardless. The interruptible power supply is an interesting option, but increases costs significantly. A study was performed to find the best suitable UPS, see appendix L, and the result was a machine that costs \$95. A more affordable solution needs to be found.

None of the solutions are adequate.

### 5.2.2 Custom UPS

To avoid the high cost price of store-bought UPS, it was hypothesized that it might also be possible to build a custom UPS using recycled electronics. The functioning of a UPS is rather straightforward: A power supply charges the batteries, and this setup is connected in parallel to the 3D printer. In case of a power outage, the power will still flow from the batteries to the printer, and thus the printer can run off the grid for a while.

#### Battery selection

It is vital to choose the correct type of battery that the context and use demands. These demands are summarized as follows: The battery should be procurable for low cost, require little to no maintenance and it should have a high

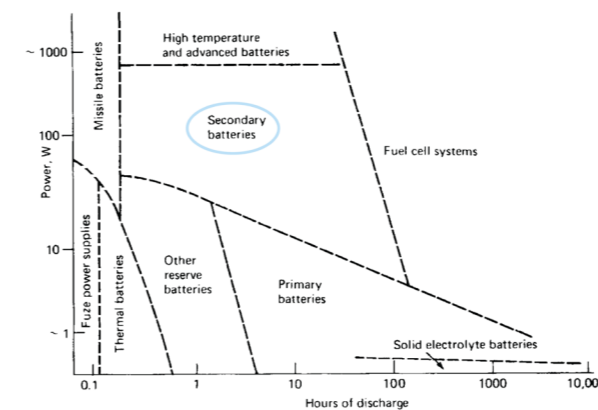


Figure 32: Application field for different types of batteries, adapted from [89]

lifetime. Moreover, it should be tolerant to overcharging and deep discharging, and preferably it should be recyclable. Lastly, it should be able to supply between 50 and 150 Watts and should allow for around one hour of discharge [88].

To make a first selection, the Handbook of Batteries [89] was consulted. As shown in figure 32, secondary batteries fit these demands the best, considering the hours of discharge and power supply.

Secondary type batteries are also generally chosen for use in a UPS. The most common types are listed in the table below, together with several properties. Only lead-acid and Li-Ion batteries are considered, as these are the most widely used, and because they require the least amount of maintenance. A lead-acid battery is on average 4 times cheaper than a Li-ion battery, but is usually also 4 to 6 times bigger and heavier. The Li-ion battery has a higher lifetime, but a major drawback is safety. Although almost all types of batteries have the risk of thermal runaways, the risk is greatest with Li-Ion batteries [90]. Problems in battery design, or improper charging, such as overcharging can lead to the batteries exploding (this resulted in a major crisis for Samsung, when users found their Galaxy Note's started exploding in 2017 [91]).

	Secondary batteries			
	Nickel-cadmium	Lead-acid	Nickel-metal hydride	Lithium-ion
Nominal cell voltage, V	1.2	2.0	1.2	4.1
Specific energy (Wh/kg)	35	35	75	150
Energy density (Wh/L)	100	70	240	400
Charge retention at 20°C (shelf life)	3-6 months	6-9 months	3-6 months	9-12 months
Calendar life, years	4-6	3-8	4-6	5+ yrs
Cycle life, cycles	400-500	200-250	400-500	1000
Operating temperature, °C	-20 to 45	-40 to 60	-20 to 45	-20 to 60
Relative cost per watt-hour (initial unit cost to consumer)	15	10	25	45

Table 8: Secondary battery characteristics, reprinted from [89]

#### Bottomline

Li-Ion batteries are four times as light, but four times as expensive as lead-acid batteries, and then there's the safety hazard. Affordability is a design driver, while battery size and weight is less important, and therefore the best solution seems to be lead-acid batteries.

Within the domain of lead-acid batteries there is also a wide range of possibilities. The main difference is between flooded and sealed batteries. Flooded batteries need to be topped up with water every 3-6 months. Moreover, they are known to slowly leak toxic and flammable hydrogen



fumes. Sealed batteries, often referred to as Valve Regulated Lead-Acid (or VLRA) batteries, do not have these problems and require no maintenance. Moreover, there are many VLRA batteries on the market that allow for deep discharge cycles. A quick comparison of these types is shown in table 9, based on data found online [92].

	Flooded	Sealed
Maintenance	High	Low
Allows deep cycle	No	Yes
Relative cost	\$	\$\$

Table 9: Comparison between flooded and sealed lead-acid batteries

**Conclusion**

A battery is required that is able to be deeply discharged, be procured for low cost, and should require little to no maintenance. The battery of choice is therefore the sealed VLRA lead-acid battery.

**Battery specifications**

Now that the type of battery has been selected, it is time to choose the correct battery specifications. Therefore, first a comparison will be made between a 12V and a 24V system, and next the required capacity will be calculated.

**12V vs 24V**

The Prusa runs at 24V, while many 3D printers run at 12V. This has implications for the battery backup system, as a 24V setup would require two lead-acid batteries instead of one. Moreover, during the field trip it was discovered that 24V components are much more difficult to acquire locally than 12V components. However, a 24V setup does have several advantages in terms of 3D printing properties. A well founded consideration needs to be made between these two setups. Insights are retrieved from Dyze Design [93].



Type	✓ Pros	✗ Cons
 12V	<ul style="list-style-type: none"> <li>Spare parts can be easily found</li> <li>Only requires a single lead-acid battery</li> </ul>	<ul style="list-style-type: none"> <li>Slower heating</li> <li>Lower motor speed and torque</li> <li>Bigger wires</li> </ul>
 24V	<ul style="list-style-type: none"> <li>Smaller wires</li> <li>Higher motor speed and torque</li> <li>Faster heating</li> </ul>	<ul style="list-style-type: none"> <li>Spare parts are difficult to find</li> <li>Requires two lead acid-batteries</li> </ul>

Table 10: Consideration between a 12V or a 24V printing and powering system

for reliability". As this setup will require only one battery it is cheaper, and because 12V parts are much more generic, this greatly improves reparability. Moreover, the higher motor speed and torque that the 24V setup enables, do not create any benefit in a 3D printing setup, as other factors, such as max extrudability, are limiting the speed more than the max RPM of the motors.

**Required battery capacity**

12V sealed lead-acid batteries come in many different capacities, ranging from 0.8 to more than 100Ah. To find the required battery capacity, a calculation tool was made in Excel. This is described in Appendix M. This tool was used to design several battery setups, for different "off-the-grid" printing times (5, 30 and 60 minutes. The results are shown in the table below:

	5 min	30 min	60 min
Average power drawn [Watt]	60.00	60.00	60.00
Voltage [V]	12.00	12.00	12.00
Average current [A]	5.00	5.00	5.00
Time [hours]	0.17	0.50	1.00
Capacity needed [Ah]	0.83	2.50	5.00
Battery maximum discharge	80%	80%	80%
C-rate	0.40	0.50	0.60
Minimum battery capacity [Ah]	2.60	6.25	10.42
Closest available battery [Ah]	3.20	7.00	12.00
Cost	\$ 11.00	\$ 15.00	\$ 30.00

Table 11: Showing different battery designs, and the battery of choice (blue)

**Conclusion**

The best suited battery is a 12V 7Ah VLRA battery, which costs an estimated \$ 15, and can power the printer off-the-grid for around 30 minutes.

**5.2.3 Testing**

To put theory into practice, several tests were performed in which a 3D printer was powered from VLRA batteries.

**Method**

To test the until now mostly undocumented feat of running a 3D printer on a battery powered setup, a few different tests were devised. In all of these tests 12V 7Ah VLRA batteries were used from the brand EnergiVm [94].

**1. Two batteries and the 24V Prusa**

First a simple demonstration test was performed, in which the 24V Prusa was powered from two 12V batteries connected in series.

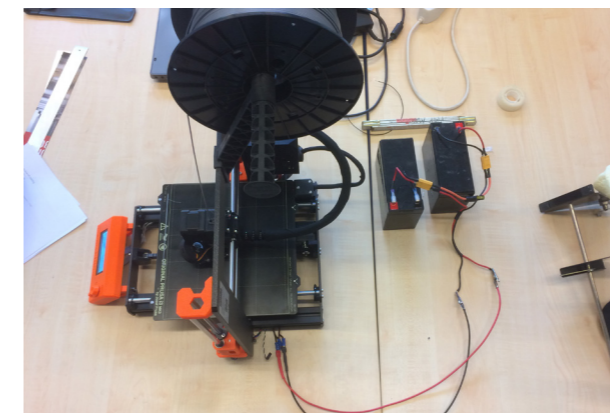


Figure 33: The first test, running the Prusa on two lead-acid batteries

**2. One battery, 12V printer and a 2A charger**

Next a more comprehensive test was conducted. Since it was decided that the printer should run on 12V, a test was setup with a 12V Anet A6 printer, a single battery and a

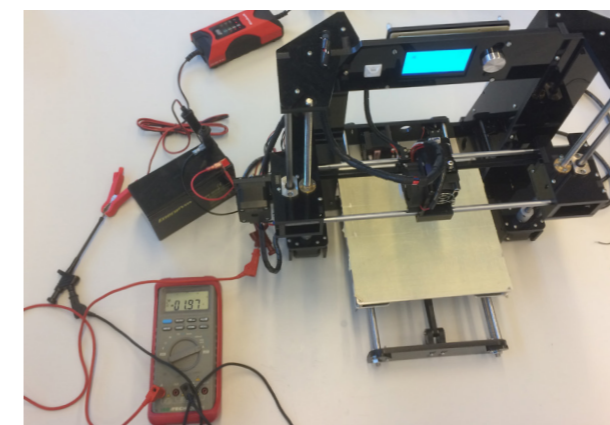


Figure 34: The second test, where a printer was powered from a single battery

12V 2A trickle charger from the brand Einkell (\$20) [95]. A multimeter was added in the circuit to measure currents.

**3. One battery, 12V printer and a 5A charger**

The third and final test was conducted to see if a stronger charger would be able to keep the battery fully charged. A 12V 5A universal charger was used, from the brand iMax [97]. During this test continuous measurements were done with two multimeters, one measuring voltage, and the other measuring current. Furthermore, the smart charger had a display of its own, showing the supplied voltage and current. Using these measurements, an extensive amount of data could be gathered.

First the printer was powered on the battery system, while being connected to the grid. This procedure was repeated, but the second time, the plug was pulled on the charger after 15 minutes, to see how long it could run off the grid.

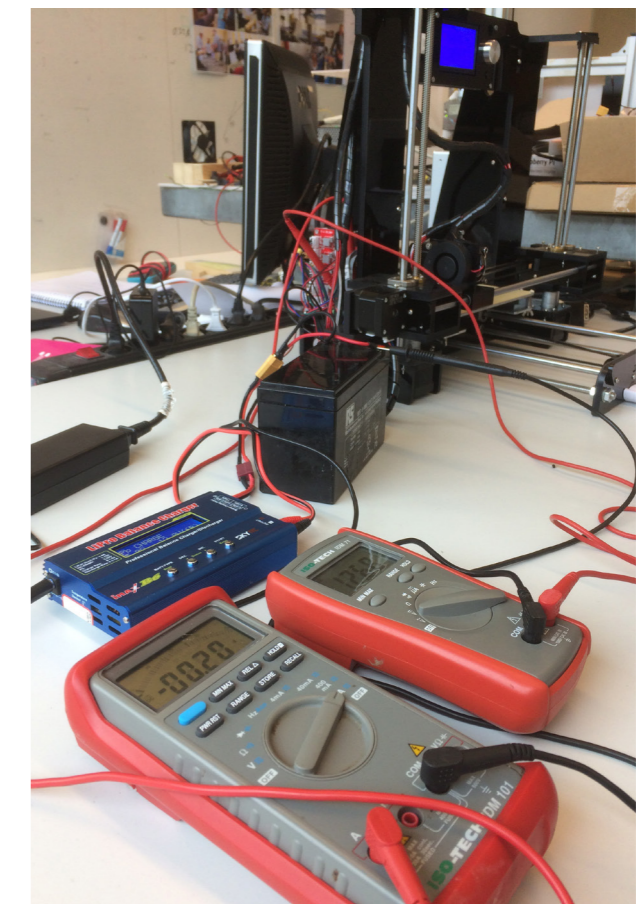


Figure 35: The third test, where extensive measurements were performed

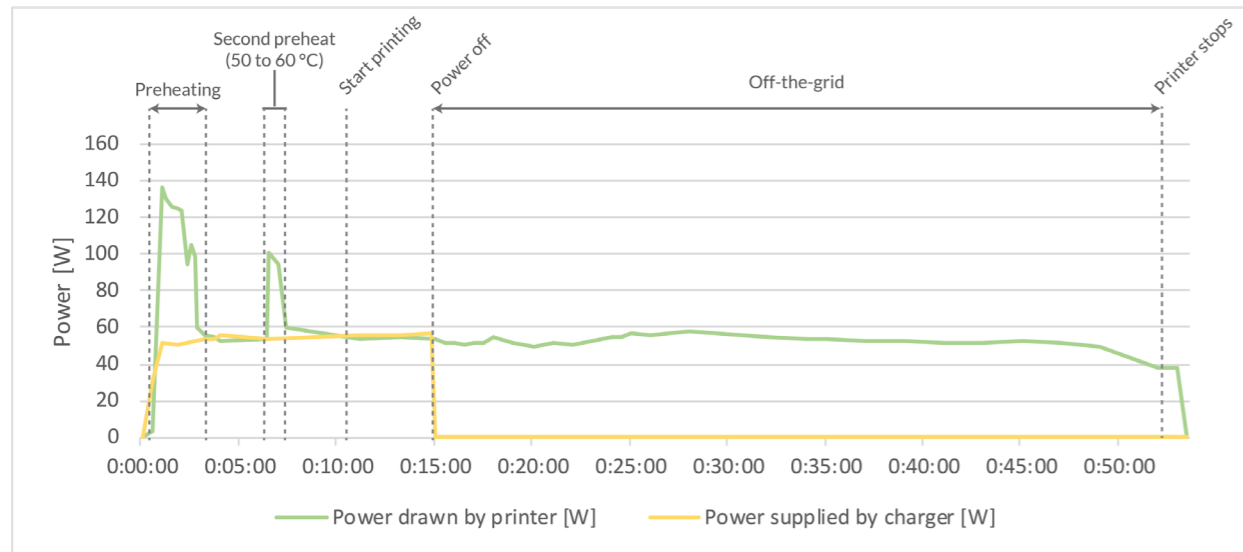


Figure 36: Showing results from the third test. After 15 minutes the power plug was pulled.

### Results

The results of all three tests are described below.

#### 1. Two batteries and the 24V Prusa

It was possible to heat the bed, and extruder and run a 30 minute print job directly from the batteries. After this time, the voltage levels started dropping rapidly, ultimately causing the printer to stop functioning. This setup was successful in demonstrating that VLRA batteries are able to power the printer off the grid for a short time.

#### 2. One battery, 12V printer and a 2A charger

While connected to the charger, the battery was able to heat the bed and extruder, and start a print job. However, when this was attempted a second time, shortly after the first try, the battery and charger system were not able to supply the printer with enough power to get the bed to the required temperature (50 °C).

The following measurements were done:

	U [V]	I [A]	P [W]
Printer idle	12.4	0.2	2.5
Motors on	12.4	0.9	11.2
Preheat	11.1	10.2	113.2
Printing	12.5	4.5	56.3

Table 12: Showing measured voltage, current and power during the second test

#### 3. One battery, 12V printer and a 5A charger

Part of the results of this test are shown in figure 36. However, much more data was gathered; this can be found in Appendix N.

### Conclusion

From the second test it can be concluded that the battery is not able to do the heatup phase twice in a row, and that the charger cannot supply enough power to keep the battery fully charged. The printer draws on average 60 Watts, during normal printing with the bed heating on, while the charger is only able to supply 30 Watts. A stronger charger must be used, that can supply a minimum of 5A, or 60 Watt.

From the third test the following conclusions were drawn:

- The charger can supply enough power for normal printing
- The charger cannot supply enough power for the heating phase
- The battery is able to power the printer off-the-grid for 40 minutes
- The battery needs at least 45 minutes to recharge from the drained state
- Once battery is drained below 10V, printer stops functioning correctly

## 5.2.4 Final design

The final design of this flexible power supply system consists of the following elements:

- **Surge protected AC/DC Converter:** A 220V to 12V AC/DC converter is needed to provide the correct voltage and current to the charger. This should be protected against power surges.
- **12V 5A smart charger:** A smart battery charger is needed that can supply enough power (minimum 60 Watt). The best solution was found to be a 12V 5A universal charger, from the brand iMax [97].
- **12V 7Ah VRLA Battery:** As described above, these sealed, maintenance free batteries meet the requirements for printing off the grid for half an hour. At 25 °C temperature, these batteries have an estimated life expectancy of 3-4 years when used as described.
- **Safety circuit:** A circuit that cuts power from the battery to the printer when the voltage level drops below 10V.
- **Power Loss Recovery:** As shortly described before, this Marlin integrated software solution, allows for continuation of printing once the power is recovered, and can therefore save prints in case of a power outage lasting longer than the 30 minute battery backup time.

#### Safety circuit

To ensure that the battery is not fully discharged in case an outage lasts longer than 30 minutes, a safety circuit needs to be integrated. This circuit should be designed to cut off the power from the battery to the printer when the battery is not able to supply the printer with enough voltage. During the second test it was found that once the voltage started dropping below 10V, the printer was not able to



Figure 37: PCB with safety circuit, designed by C. Peacock [96]

perform correctly (see appendix N). Therefore, 10V is a proper cut-off threshold.

This safety circuit can be realized in different ways, such as using a Schmitt trigger in combination with a relay, or by using a voltage switch. A readymade circuit and PCB design was found at circuitmaker [96] that can directly be used for this purpose. The cut-off voltage is easily programmable.

#### Cost

In the Netherlands a 12V 7Ah VLRA battery costs around \$15 [98]. The converter and charger can be acquired for \$25 from AliExpress [97], and the safety circuit PCB costs an estimated \$5 making the total cost of this solution \$45. According to Karl [42], similar parts can be found locally in Nairobi, Kenya, for less.

Part	Function	Sourcing	Cost
12V 7Ah VLRA Battery	Battery	Local	\$15.00
12V 5A Smart charger	Charger	Import	\$25.00
Low voltage cut-off PCB	Safety	Local	\$5.00
<b>Total</b>			<b>\$45.00</b>

Table 13: Showing final cost estimation for this solution



Figure 38: Showing basic setup of the final design

## Chapter 5.3

# Dust and heat

The printer should be able to deal with excessive dust and high temperatures

In this chapter different methods of dust prevention as well as means to fight overheating are designed and tested.

### Requirements

- The extruder should include a dust filter to prevent dust from entering the nozzle
- The electronics should be protected from dust (IP5)
- Dust filters should be able to stop dust particles down to 10 μm
- The electronics should be properly cooled to prevent overheating issues

### 5.3.1 Type of enclosure

The first consideration to be made is whether to go for a complete enclosure, where the entire build chamber is enclosed, or for a partial enclosure where only the electronics are enclosed.

#### Full enclosure

In this case the entire print environment, including extruder is enclosed. This type of enclosure is commonly found in the Prosumer printer segment (> \$ 3000), and a higher end enclosure is always found in industrial printers. A full enclosure helps to prevent dust from entering the print environment, extruder and electronics. As an added benefit, it also helps to control factors like ambient temperature and humidity, which in turn leads to better

control over print quality.

#### Partial enclosure

A more affordable solution is to only enclose only the elements that have the highest risk of being affected by the dust, e.g. the electronics. An effective method was demonstrated by Savonen, et al. [10]. They enclosed their electronics and provided air circulation by means of a fan with dust filter.

#### Conclusion

To keep cost price at a minimum, a partial enclosure is considered optimal for this project. However, this enclosure does not protect the extruder from dust particles. Therefore extra attention should be given to how the extruder can be protected in some way, for instance by passing the filament through a dust filter of some kind.

**The partial enclosure is considered optimal.**


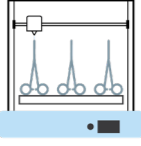
Type	✓ Pros	✗ Cons
 Full enclosure	<ul style="list-style-type: none"> <li>• Controlled printing environment</li> <li>• Effective dust prevention</li> <li>• Could increase sterility of printed parts</li> </ul>	<ul style="list-style-type: none"> <li>• Expensive</li> <li>• Complicated</li> </ul>
 Partial enclosure	<ul style="list-style-type: none"> <li>• Affordable</li> <li>• Effective against overheating electronics</li> </ul>	<ul style="list-style-type: none"> <li>• Does not protect extruder from dust</li> <li>• Does not protect bearings and other greased components from dust</li> </ul>

Table 14: Discussing product use with a biomedical engineer at Kenyatta National Hospital, Nairobi.

### 5.3.2 Filament dust filter

It is known that over time dust can start to collect on a strand of filament, and if this enters the extruder, it will cause accumulation of particles in the nozzle and eventually lead to partial or full clogs. These clogs can lead to printing defects or can even cause the printer to stop functioning altogether. The context analysis showed that Kenya experiences excessive dust, and therefore a solution needs to be found.

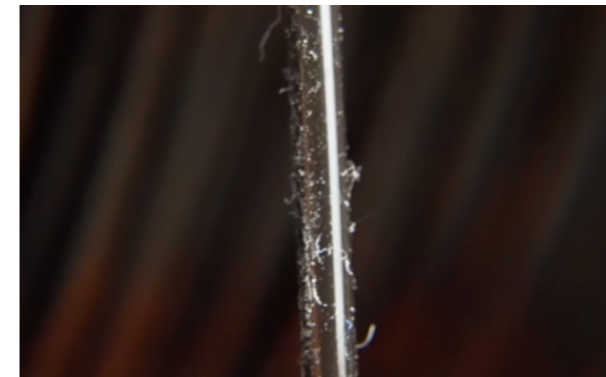


Figure 39: Dust can easily collect on a strand of filament

#### First prototype

To prevent dust from entering the extruder, a dust filter can be added on top of the extruder. A simple filter was designed which encases a piece of foam. The filament passes through this foam, before entering the nozzle and it was hypothesized this would wipe off any dust that might be sticking to the filament.

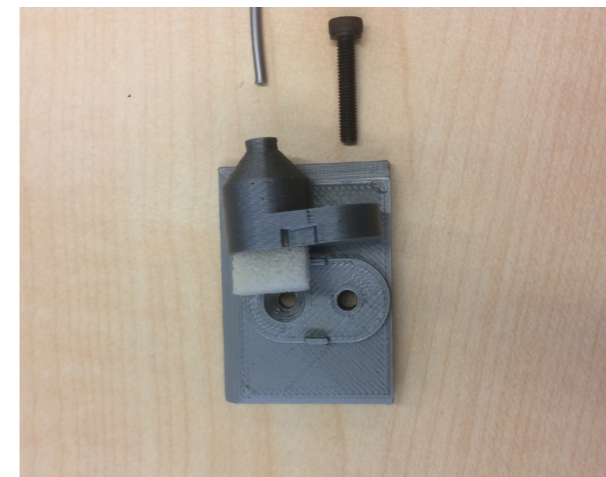


Figure 40: Basic setup of the first prototype dust filter

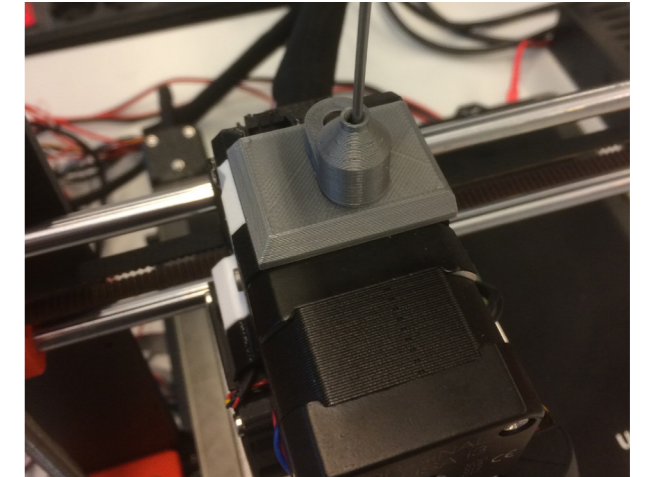


Figure 42: The dust filter mounted on top of the extruder

During the first tests the foam was successful in wiping off any dust stuck to the filament. However, in the act of pushing the filament through the foam, it was not uncommon for a small piece of the foam to become dislodged, which could then enter the extruder together with the filament, and cause clogs. Moreover, the dense foam resulted in a bit of filament drag (0.7N, see figure 41), which should be avoided at all times, because it can disturb proper extrusion and retraction rates, and thus printing quality.



Figure 41: Measuring filament drag with a force meter

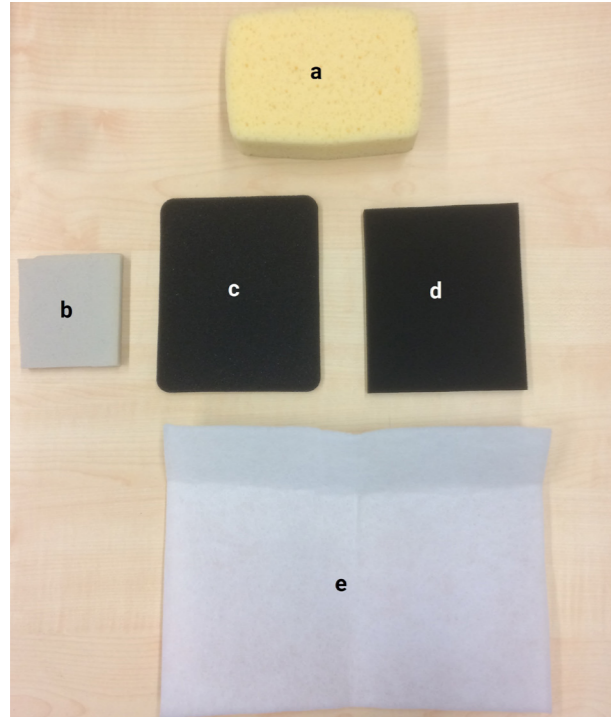


Figure 43: Different filter materials tested. a=Regular sponge, b=Soft packing foam, c=Philips spongefilter [99], d=Philips motorfilter [100], e=Scanpart microfilter [101]

### Testing different materials and methods

Several different foam materials were tested for effective dust cleaning as well as minimal filament drag. For this mostly vacuum cleaner dust filters were used, as shown in figure 43. Besides different materials, several different

ways of enclosing the foam were also tested. These methods include (1) using a single piece of foam, (2) using two smaller pieces of foam sandwiched together, and (3) rolling up a thin piece of foam in the form of a cylinder with a hole in the middle. It was hypothesized that the first method would result in the highest filament drag, and would increase the risk of pieces of foam becoming dislodged.

### Results

The Scanpart microfilter (material e) turned out to be most effective against dust, and also resulted in the least amount of filament drag (0N measured). The best method for placing the foam in the casing was found to be method 3, by rolling a thin piece of the filter in a cylinder shape, a small hole is left in the middle, which allows the filament to pass through easily, without dislodging any foam materials.

### Final design

The final design of this dust filter consists of the following elements:

- Scanpart microfilter (or similar)
- 3D printed enclosure
- M3 screw

### Cost

The final cost price for this solution is estimated at \$1.50.

Part	Function	Sourcing	Cost
3D printed enclosure	Enclosure	Local	\$0.50
Foam filter	Filter dust	Local	\$1.00
<b>Total</b>			<b>\$1.50</b>

Table 15: Showing final cost estimation for this solution

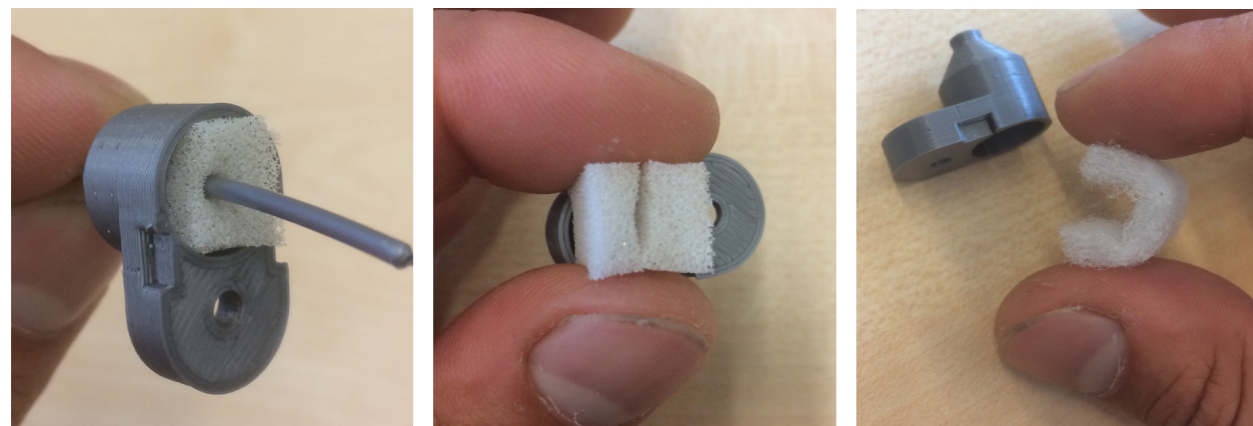
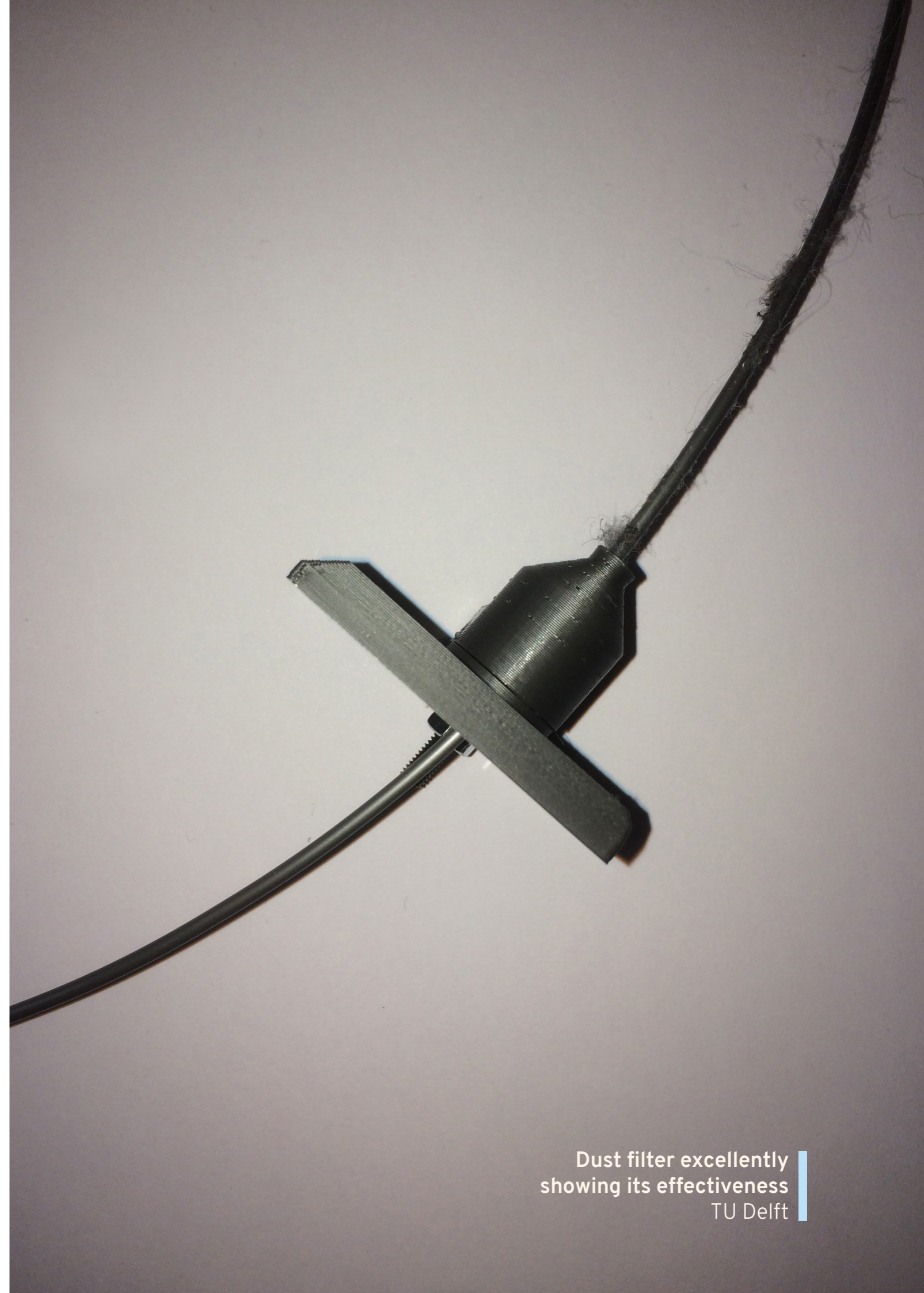


Figure 44: Different methods used to prepare the foam. From left to right: Using a single piece, two pieces sandwiched together or a single piece rolled up.



Dust filter excellently showing its effectiveness  
TU Delft

### 5.3.3 Electronics enclosure

From the analysis it followed that the electronics need to be properly enclosed, to stop dust from entering and accumulating, which can cause overheating issues resulting in the board breaking down. The controller board is one of the more expensive parts of the 3D printer, so proper dust protection and cooling is very important. The current Prusa enclosure does not stop dust from entering, and supports no way of cooling. This section described the steps that were undertaken to design an IP5 electronics enclosure.

#### First attempt: Wooden enclosure

A first enclosure for the electronics was built using wooden panels. Air flow was created with two fans, the lower blowing air in, the upper blowing air out. Dust filters made from tights were placed in front of the fans.

#### Results

- Temperature measurements during a print job showed a temperature difference of 10 °C when the fans were switched on, as opposed to the fans switched off.
- Low-end dust filters seem to stop some dust from entering, but do not ensure a P5 protection
- Large hole at the bottom of the enclosure where cables run through, is a weakness where dust can enter
- It was very tedious to hook up the cables to the board in the small enclosure, see figure 45
- There was no way to attach the enclosure to the frame



Figure 46: Showing first prototype of a wooden laser cut enclosure

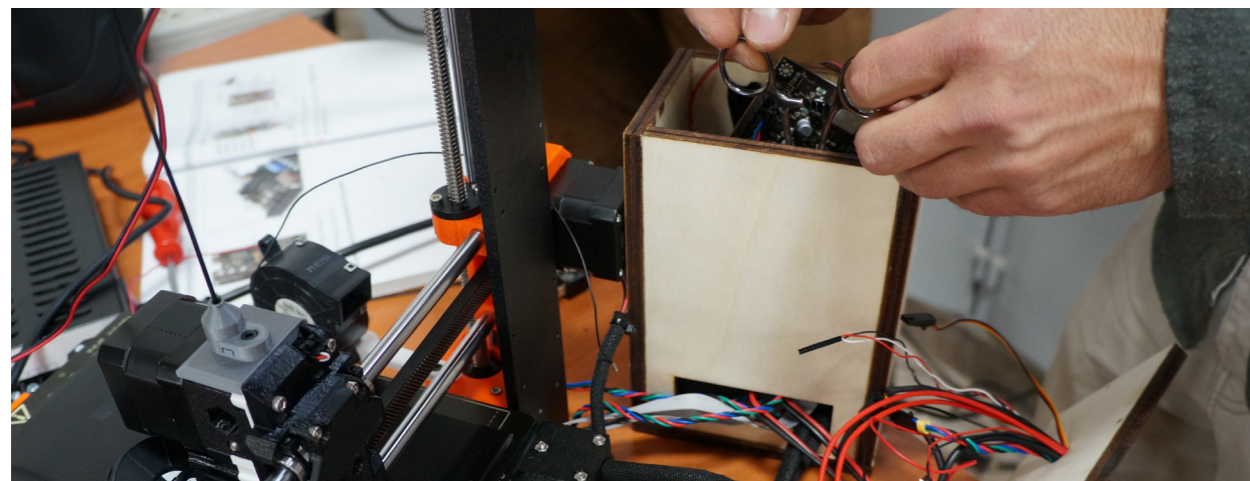


Figure 45: This image perfectly illustrates how frustratingly difficult it was to attach the wires to the controller board. The pliers were a necessity..

#### Second attempt: 3D printed enclosure

A new enclosure was designed, taking into account the problems encountered with the first attempt.

This enclosure was designed to be 3D printed, as this allows for more design freedom. In this design the following areas are taken into special consideration:

- Improving cable management
- Allow for easy power supply plug-in
- Cooling
- Preventing dust

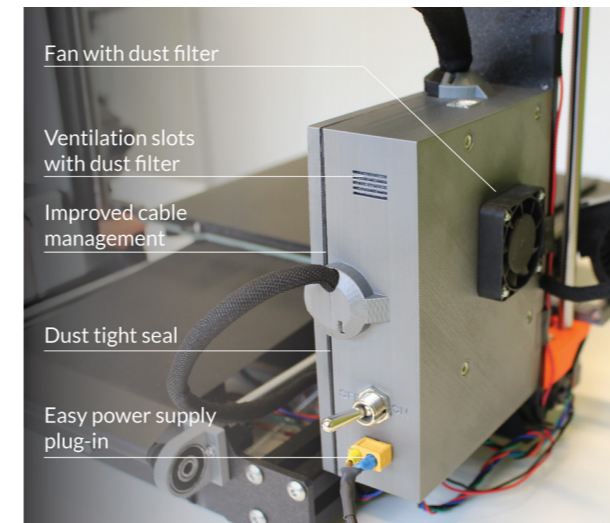


Figure 47: Showing the main features of the new and improvement enclosure

#### Improving cable management

The cables from the extruder and heatbed run in through connectors, similar to the original electronics enclosure designed by Prusa. The other cables coming from the motors and LCD enter the bottom of the enclosure, and are sealed by a foam padding. This foam padding acts as a

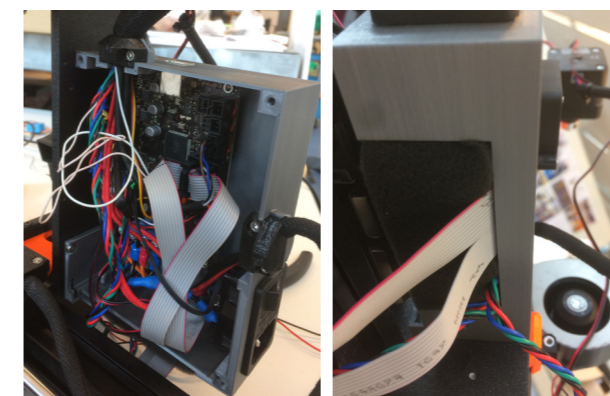


Figure 48: Good cable access (left), and tight dust sealing with foam (right)

dust filter. The new enclosure was designed to be closed with a lid that can be easily removed with three screws. This allows for much better cable accessibility.

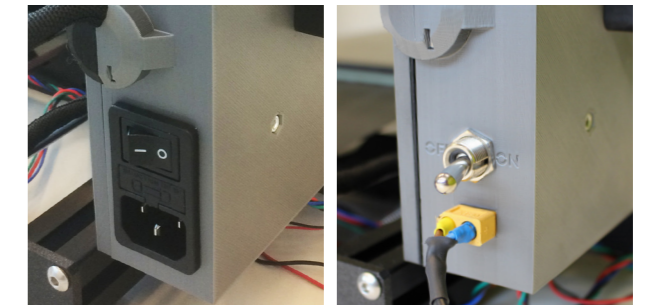


Figure 49: First iteration (left), and final design with XT60 plug (right)

#### Allow for easy power supply plug-in

To accommodate for the flexible power supply, it is important that the power supply can be connected to the electronics with ease, without having to open up the entire enclosure. The first solution was embodied using a regular power connector with integrated switch, as seen in figure 49, on the left. However, this soon proved to be a mistake, as these connectors are commonly used for 220 VAC, which would immediately fry the electronics. Therefore, a second iteration was made, where an XT60 plug was used for the power supply connection, as shown in figure 49, on the right.

#### Cooling

For this design a single fan was chosen for cooling. Using two fans might increase airflow, but also brings in a risk of extra dust intake. If the fan blowing air out of the enclosure produces a higher airflow than the fan blowing air in, the enclosure will have a negative pressure, and dust will be sucked in from every cavity. Choosing a single fan removes this uncertainty, and provides enough air flow as it is. The fan is placed directly behind and in the center of the electronics board, and also includes a dust filter. Ventilation slots were added on the side, at the top of the enclosure, to ensure proper air flow, as shown in figure 47.

**Preventing dust**

To prevent dust from entering the enclosure, in accordance with an IP5 rating, it is important that all gaps and cavities are sealed as tightly as possible, and that cooling air flow is forced through dust filters.

**Rubber seal**

A rubber 1mm thick seal was attached on the lid. This strategy is also commonly used to make enclosures waterproof, and is therefore an excellent solution to prevent dust from entering.

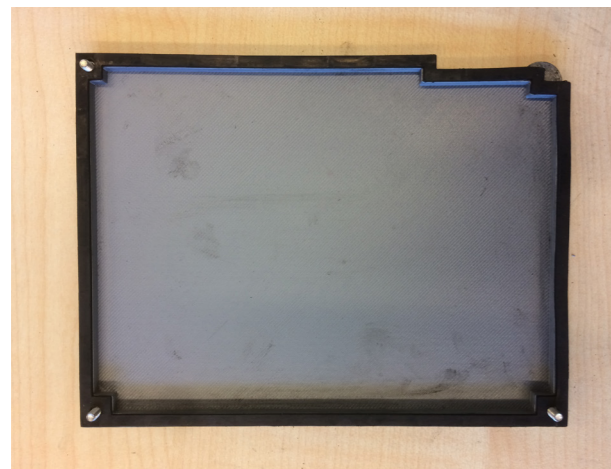


Figure 52: Showing the enclosure lid with rubber seal

**Finding the correct dust filter**

The solution of cooling the electronics with a fan also adds the risk of dust being blown into the enclosure. To stop this from happening, a dust filter should be placed in front of the fan.

It is important to find a dust filter that can prevent fine particles from entering the electronics. However, during preliminary testing it was found that some filters block the air flow from the fan completely, which does not only hinder proper cooling, but also greatly decreases life expectancy of the fan.

Therefore a simple test was devised, in which threads of fine red fabric were attached to the dust filter guard to visualize air flow; the higher the threads rise, the better the air flow. A full report on this test can be found in appendix P.

With this method five different dust filters were tested for air flow, as shown in figures 51 and 51.

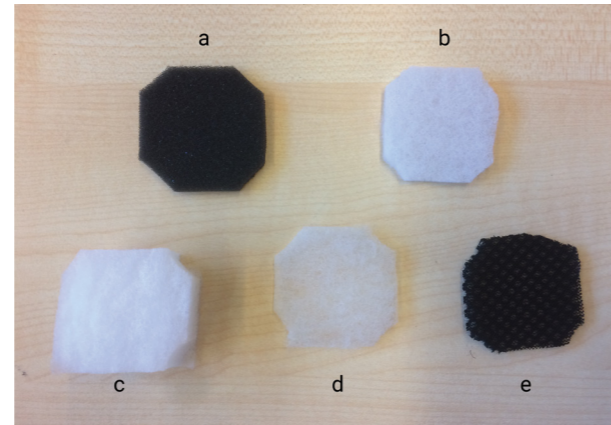


Figure 50: a=Philips spongefilter [99], b=Scanpart microfilter [101], c=Professional M5 filter [102], d=1/5th thickness professional M5 filter [102], e=mesh material that was lying around the workspace

**Results**

Material b was found to be the best solution, as it has excellent dust filter capabilities, but also provides decent airflow. Material e, providing optimal airflow, was regarded insufficient in collecting dust. A full report on this test can be found in appendix O.

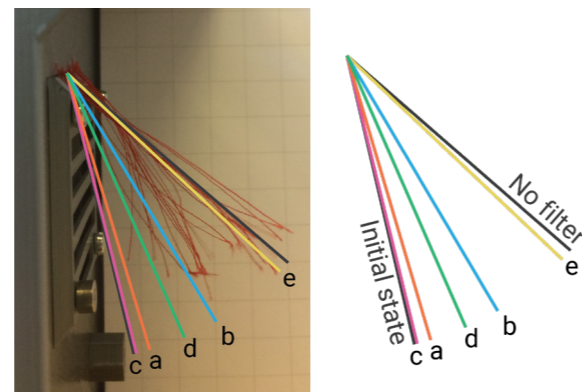


Figure 51: Visualized air flow for different dust filters that were tested

**Testing**

**Cooling**

A one hour print job was done while measuring the enclosure temperature with a thermistor on the electronics board. This was done for the original Prusa enclosure, as well as the new and improved enclosure. The results are shown in figure 54. It shows that the new enclosure helps to decrease the electronics temperature from a maximum of 46 to 34 °C. It can be seen that the temperature rises, but then stabilizes after around half an hour at approximately 34.5 °C. Ambient temperature during this test were around 21°C.

**Heavy dust test**

One of the requirements is to make sure the enclosure meets an IP5 rating. IP5 means “Ingress of dust is not entirely prevented, but it must not enter in sufficient quantity to interfere with the satisfactory operation of the equipment” [103]. The test method used in the industry for this IP rating involves exposing the enclosure to fine-grained talcum powder in a dust chamber for 2 to 8 hours [104].



Figure 53: Final dust test setup of the enclosure in a sandblasting chamber

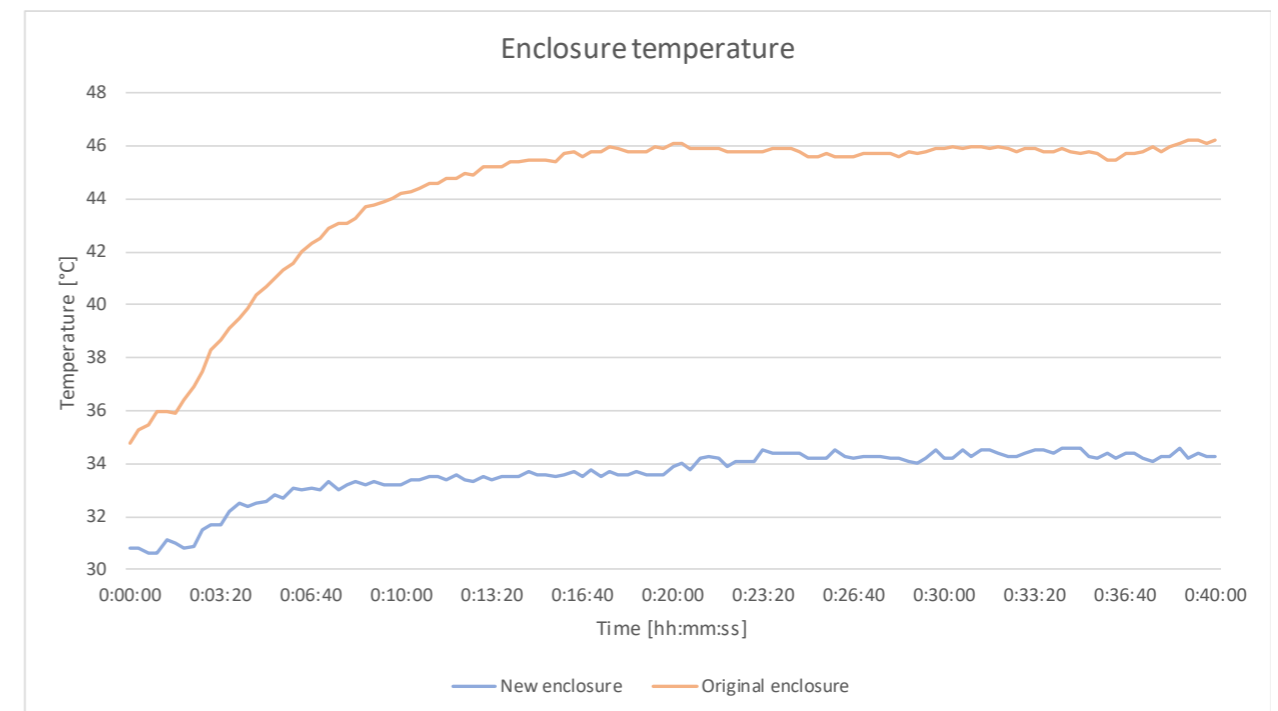


Figure 54: Graph clearly showing the improved cooling effects of the new enclosure (temperatures are reduced by approximately 12 degrees)

A similar test was devised, in which a sand blasting machine was used to function as a dust chamber. Incoming dust particles were captured by a sheet of red sticking vinyl. A full report of this test can be found in appendix P.

As seen in the picture on the right, a thin layer of fine dust collected on the outside of the enclosure after the testing. None of this fine dust was found inside the enclosure after opening. However, some of the grain sized glass beads did manage to get inside, as shown on figure 55. This was probably due to a weak spot in the bottom right corner of the lid. This could be solved by replacing this latch with a screw, like in the other corners. However, this would reduce ease of access to the electronics.



Figure 55: Results from the dust test. White circles indicate penetrated particles

### Final design

The final enclosure consists of the following elements:

- 3D printed housing
- Rubber seal
- On/off switch
- XT60 power connector
- 12V 40x40 Fan
- Dust filters
- Ventilation slots with dust filter

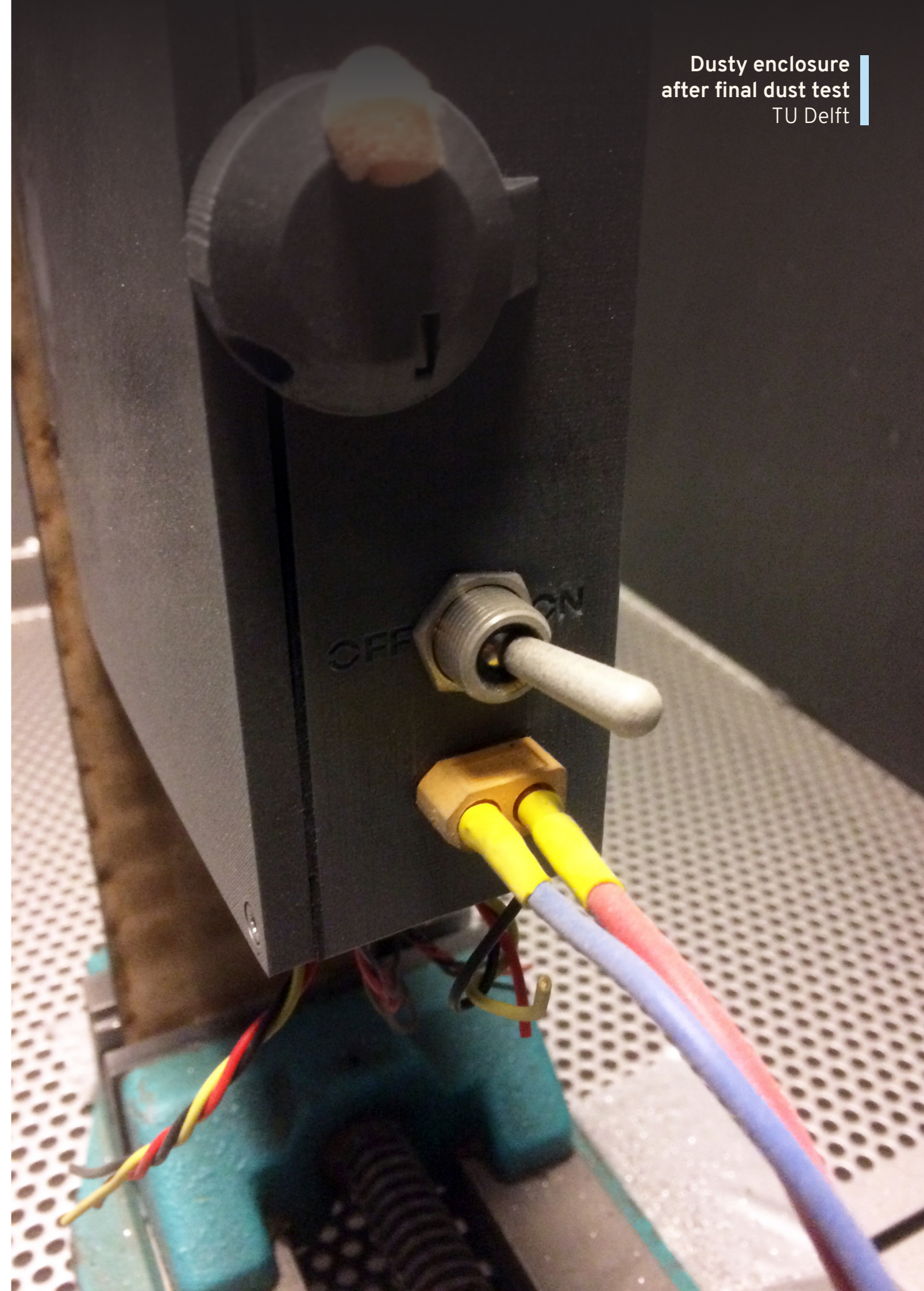
### Cost

The total cost of this solution is estimated at \$5.

Part	Function	Sourcing	Cost
40x40 12V brushless fan	Cooling	Local	\$2.50
3D printed part	Main housing	Local	\$2.30
XT60 connector	Power	Local	\$0.50
Dust filters	Prevent dust	Local	\$1.00
Rubber seal	Prevent dust	Local	\$0.20
On/off switch	Control	Local	\$0.50
<b>Total</b>			<b>\$7.00</b>

Table 16: Showing cost estimation of the electronics enclosure

Dusty enclosure  
after final dust test  
TU Delft



## Chapter 5.4

# ∞ Continuous printing

The printer should be able to maintain a maximum uptime

Great effort has gone into finding a solution for this challenge. The different steps undertaken to get there are described in this chapter.

Before diving into finding solutions, it is important to first consider whether continuous printing is really better than the conventional method of batch printing.

Note: This first section describes the process up to the start of the embodiment. To skip directly to the embodiment, visit chapter 5.4.3 on page 82.

### 5.4.1 Continuous or batches

Currently every print needs to be manually removed before a new print job can be setup. Comparing this with a regular printer would be like having to manually remove every sheet of paper, before the printer can continue with printing the next sheet. To ensure a high uptime with a 3D printer it is conventional to produce batches of parts. However, there are many downsides to this. Therefore, a new solution is hypothesized: Continuous printing.

#### Batch tray printing

This is the easiest solution, since this method is what most 3D printers can already do. By stacking multiple prints on a single tray (or print bed), it is possible to print multiple objects in one job. This has its downsides however, since

it will result in longer cooling time per layer, and different positions on the bed will influence local printing condition, all in all resulting in inconsistencies between parts, as well as inconsistencies within parts.

#### Continuous printing

By introducing a system that is able to eject parts, there is no limit in amount of parts, less manual labor is required and there are fewer inconsistencies. Moreover, this allows for the introduction of a print queue, where parts can be remotely added to the queue.

#### Conclusion

The continuous printing system is preferable over the more traditional batch tray printing since it enables a much higher uptime. Using this system can allow the operator to print 24/7, whereas this is not possible with batch tray printing. Moreover, the ability to combine this system with a print queue makes it ideal for the given context, as it greatly increases ease of use, and greatly minimizes manual labor, since it is no longer needed to manually prepare the printer for new print jobs. However, such a system is not readily available, so it needs to be designed, and this will bring in considerable challenges.

The continuous printing system is preferable.

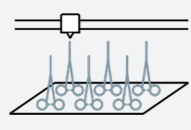
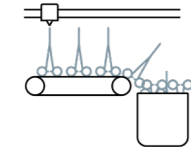
Type	✓ Pros	✗ Cons
 <p>Batch printing</p>	<ul style="list-style-type: none"> <li>Simple solution</li> <li>Easy implementation</li> <li>No added costs</li> </ul>	<ul style="list-style-type: none"> <li>Inconsistencies within parts</li> <li>Inconsistencies between parts</li> <li>Only low volume possible</li> <li>Intensive manual labor required</li> </ul>
 <p>Continuous printing</p>	<ul style="list-style-type: none"> <li>Unlimited amount of parts</li> <li>Fewer inconsistencies</li> <li>Less manual labor per part</li> <li>Possibility of setting up a print queue</li> <li>Higher profits</li> </ul>	<ul style="list-style-type: none"> <li>Difficult to implement</li> <li>High risk involved, since it can introduce new challenges</li> <li>Higher cost</li> </ul>

Table 17: Considering whether to use conventional batch printing or continuous printing

### 5.4.2 Ideation

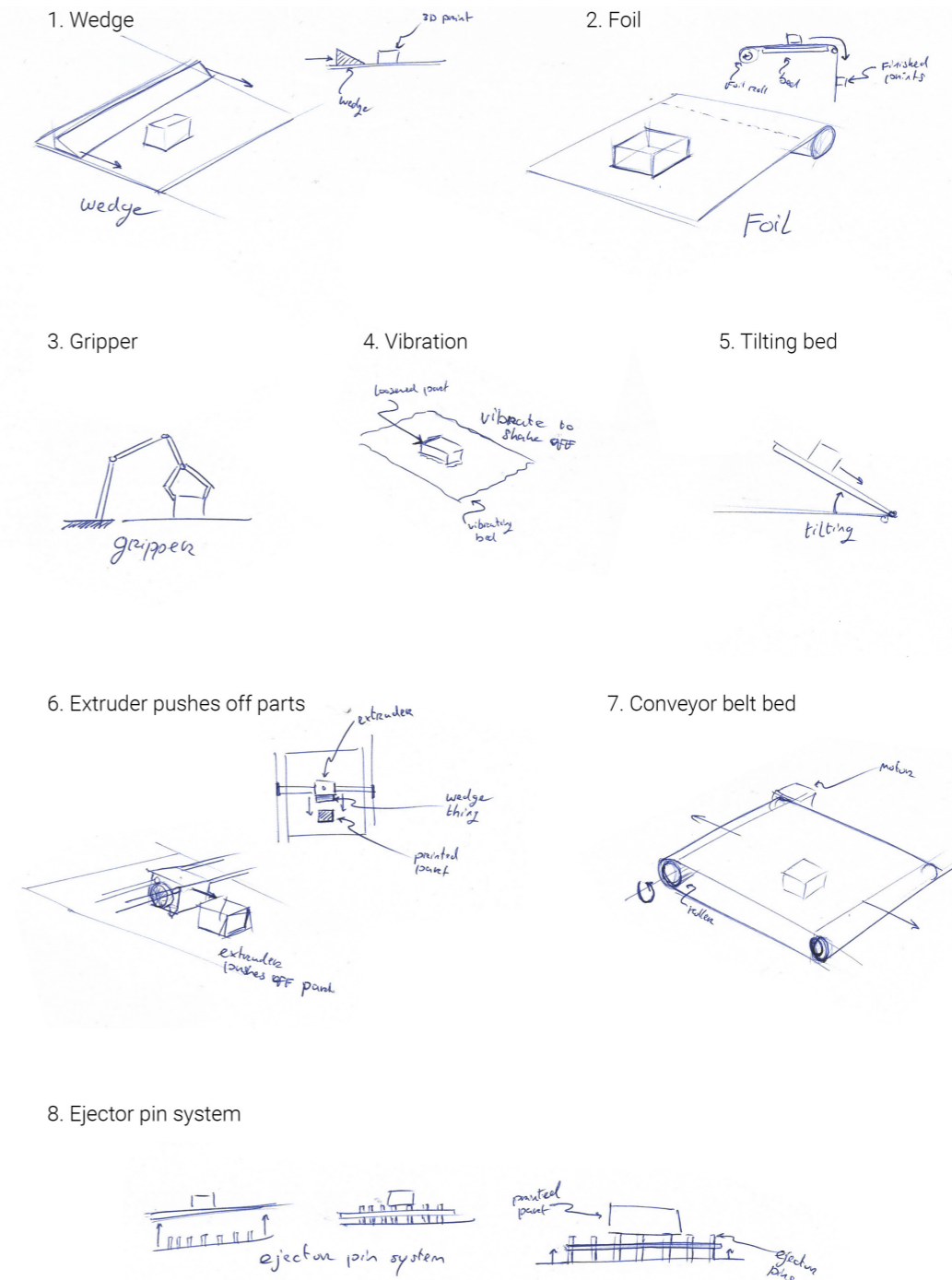


Figure 56: Results of a preliminary ideation session



### Discarded solutions

Many of these ideas can be quickly discarded, as they are unsuitable for this project. The ideas 3 to 5 (gripper, vibration and tilting) are considered either unfeasible or overengineered. Other ideas were given some more attention prior to being discarded.

#### Ejector pin system

The ejector pin system utilizes pins to eject parts, this same method is used in injection molding machines. The concept has been developed by Loop3D [105], and presumably this method works quite effectively to dislodge the parts. However, this system requires some precision engineered components and would greatly increase the cost price of the system. Moreover, implementing this system would require a complete redesigned printer, and thus, does not fit in the strategy of this project.

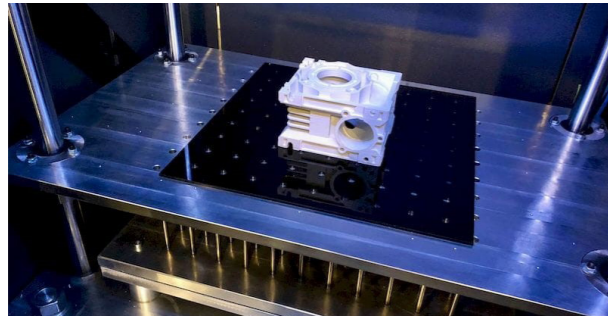


Figure 57: Ejector pin system, reprinted from [105]

#### Printing on foil

Another strategy involves printing on a piece of plastic, which can be rolled off the bed once the print is finished. This invention was first shown by two students at Penn state university [106], and later also adopted by Stratasys for their continuous printing system [107]. The plastic

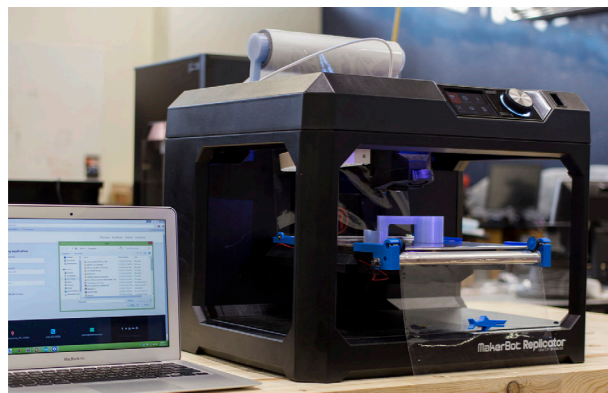


Figure 58: Printing on foil, reprinted from [106]

foil is sucked tightly on the print bed by a vacuum system. The costs involved in this concept are rendered too high for the envisioned printer. Another obvious downside of the concept is that it requires rolls of special plastic foil, and since supply chains are a big problem in the context of Africa, this would complicate matters heavily.

### A first look at the best fitting solutions

It seems that the most fitting solutions for this project are the following:

- Wedge
- Conveyor belt bed
- Extruder pushes off parts

A quick first look analysis will be performed prior to a more in-depth analysis.

#### Wedge system

A sharp metallic wedge can be used to scrape the print of the print bed. A concept where the wedge sweeps over the print bed has been successfully demonstrated by NVBots [108]. This concept was later also patented in 2016 [109].

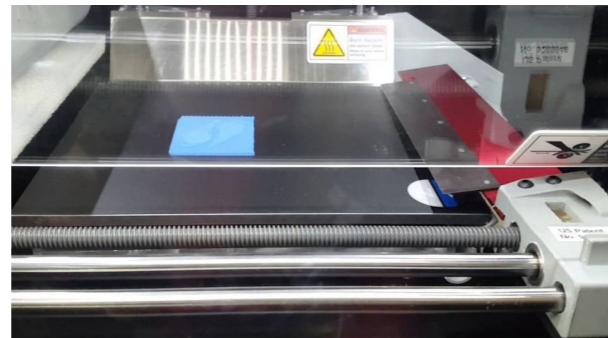


Figure 59: Wedge system, as demonstrated by NVBots [108]

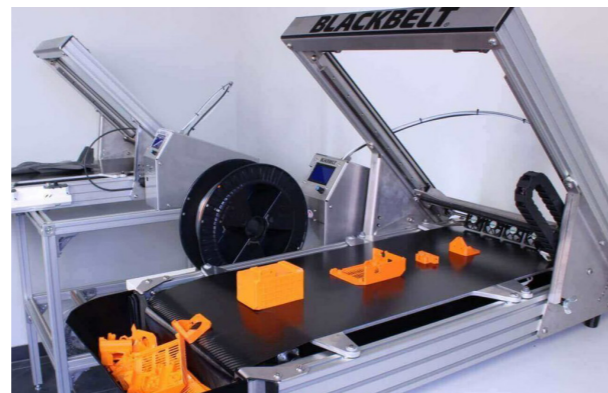


Figure 60: Blackbelt printer producing continuously, reprinted from [111]

#### Conveyor belt bed

Using a conveyor belt for the y-axis, it is possible to eject parts by rolling them off the print bed. This has previously been done by Makerbot (US) [110], BlackBelt (NL) [111], Robotfactory (IT) [112] and a Maker enthusiast on Hackaday.io [113]. Makerbot later went on to patent their solution in 2012 [114].

#### Use extruder to push off prints

Many attempts have been made to automatically eject parts by pushing them off with the extruder gantry. This might seem like a good solution, as it utilizes the hardware already onboard the printer, and therefore only requires some software tweaking. However, excessive forces can be expected when pushing off a print from the print bed, which might damage the frame, and might skew the axes, rendering the printer permanently unusable.

#### Conclusion

The conveyor belt, and wedge solutions both have been successfully demonstrated, with small as well as big parts. Using the extruder to push off parts seems to be an unreliable method which would only work with smaller parts, and can potentially cause damage to the frame or extruder, therefore this method is discarded.

### Conveyor belt system

A quick design was drawn up of how a conveyor belt system could be implemented in the Prusa printer. In this design the Y-axis movement is created by movement of the belt.

#### Foreseeable challenges

Foreseeable challenges include maintaining a flat surface, proper bed adhesion and belt to drum slipping contact. But by far the biggest foreseeable challenge is warping of the belt. Bottom layers of printed parts will cool down and will “want” to shrink. If the bed does not provide adequate stiffness to fight this shrinkage, the bed will be crumpled up, and the part will warp. One particular open source project “White Knight 3D printer” [115], has solved this problem by using a belt made from solid stainless steel (~0.1mm). In online communication with the designer, he indicated to have no warping issues [115]. The downside of this concept is cost and procurability. The cost of a single stainless steel belt is around \$ 800, quoted by a Dutch manufacturer [116]. This does not include the pulleys and suspension system.

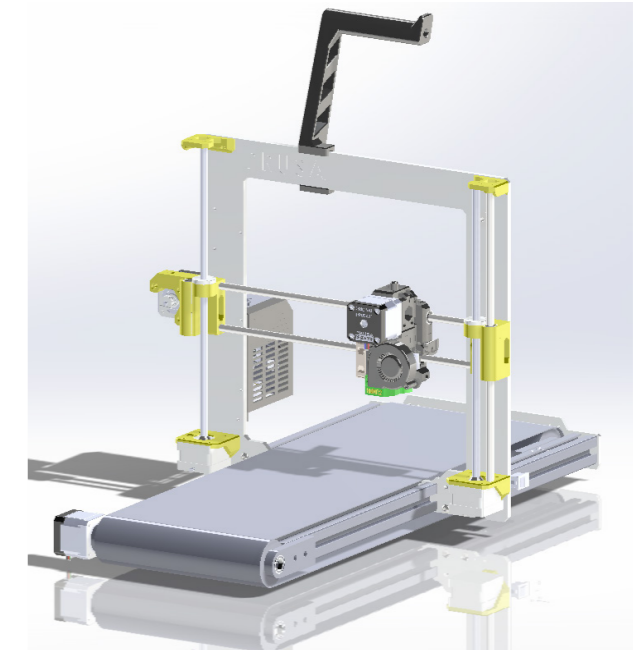


Figure 61: A first rough design of a Prusa printer with conveyor belt system

#### Patent

A github user pointed out that the current design is infringing a patent by Makerbot, since they claim “In yet another example, the conveyer 104 may, by movement of the sheet 118 of material, control movement in one axis (e.g., the y-axis), while the extruder 106 moves in the z-axis as well as one axis in the plane of the sheet.” [114]. This exactly describes the design above. A solution to this problem is by inclining the Z axis, making it a Z' axis, which is actually a combination between Z and Y axis. It is no surprise that all commercial belt printers use this inclined setup [111, 112, 115].

#### Conclusion

The conveyor belt system introduces many exciting opportunities, and seems like the most effective solution in terms of being able to dislodge parts, and maximizing output speed. However, adding this concept to the Prusa printer will require significant modifications of the entire setup (including inclining the Z axis). Many original frame parts will need to be custom made in order to accommodate for the belt system. Moreover, a custom steel belt will be very hard to acquire in or ship to Nairobi. All in all it seems that the belt system seems far from the optimal solution for the context of Africa, as it requires special parts, high customization and lastly, it also demands more time than is available in the context of this project.

### 5.4.3 Rapid prototyping

As shown in the previous chapter, the belt system is not a viable solution. The best approach seems to be the wedge system. This solution is in line with the KISS principle (Keep It Simple, Stupid), as it can be introduced in the Prusa with minimal adjustments. Moreover, this solution is very affordable, and does not require any special parts, creating a much better match with the African context.

This system will be designed through a series of rapid prototypes.

#### Method

Several quick prototypes were built and tested to see how effective they were in terms of dislodging 3D printed parts from the bed.

#### Attempt 1: Aluminum wall

The first attempt consists of a simple wall made from 5mm thick aluminum, which is placed against the frame of the printer. The part was rammed against this wall in an attempt to dislodge it from the build plate.

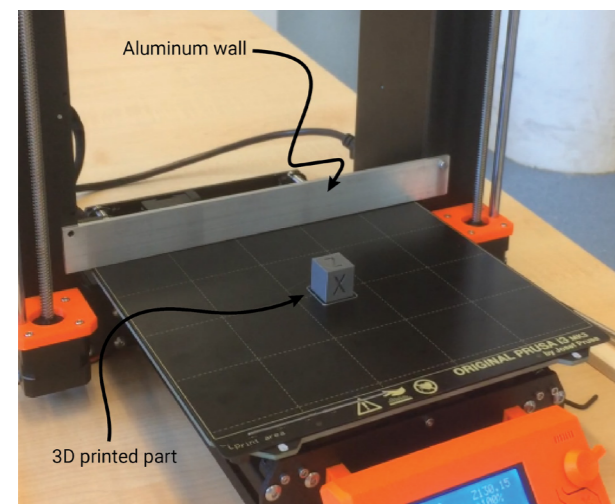


Figure 62: Showing attempt 1, using a simple aluminum wall

#### Attempt 2: Metal wedge 20°

The second attempt was to use a thin steel wedge to dislodge the part from the bed. This wedge was made from 0.5mm stainless steel, which was given a bent parallel to the long edge, in order to increase the stiffness. It was sharpened with regular sanding paper, and positioned at an angle of 20 degrees with the bed. The wedge was pressed on the bed by two springs, as seen in the figure below.

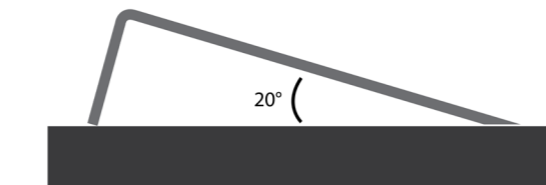
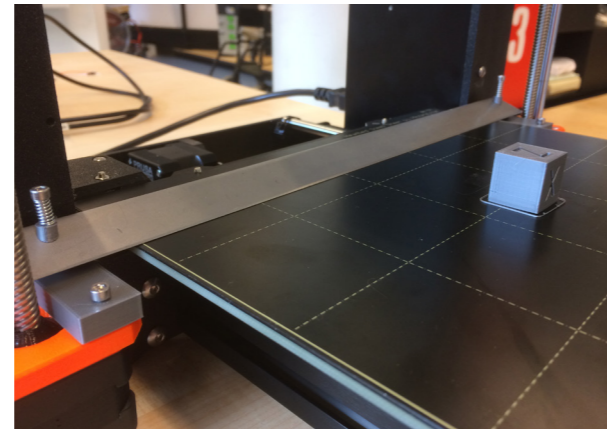


Figure 63: The setup of attempt two, a steel wedge under a 20 degree angle

#### Attempt 3: Steel-plastic wedge 10°

Another attempt was done by making a composite wedge from a 0.5mm steel sheet, bent in the same way, but under a 10° angle, and a sheet of 0.5mm acrylic plastic. This last part was sanded down carefully to provide it with a sharp edge, which turned out to be very tricky (4 blades were lost in the process).



Figure 64: Final attempt uses an acrylic-steel wedge under a 10 degree angle

### Results

#### Attempt 1: Aluminum wall

As expected, the aluminum wall was not able to dislodge the part. Instead the motor skipped steps while trying to move the bed. Considering this is such a small part, it is not a good result.

#### Attempt 2: Metal wedge 20°

The sharpened wedge was also not able to dislodge the part. Again the motor skipped steps as it would try to move the bed. Another attempt was performed with the wedge test, in which the bed temperature was raised to 100 degrees. This time the part was successfully dislodged, however, the first few layers were also slightly deformed due to overheating of the bed, so this is not a viable solution. It was also observed that the sharp metal made scratches on the build plate. This is unwanted, as over time it will scrape off the PEI coating, ruining bed adhesion properties.

#### Attempt 3: Steel-plastic wedge 10°

The results were a little more positive this time. First of all, the acrylic wedge did not leave any scratches on the build plate. Moreover, it was successful in dislodging a test print this time. One little adjustment was made to aid in this process of dislodging the part: The printed part was oriented with its corner towards the wedge, making it much easier to dislodge. Another improvement was that the flexible properties of the acrylic sheet allowed it to be slightly pushed down on the bed, making the angle even smaller than 10°. However, the results were still not promising enough to stop here.

#### Trying a different bed

One of the biggest challenges until now was that the parts stick to the bed too much. During research the author stumbled upon a new type of bed that offers excellent adhesion when it is hot, but allows parts to be removed with ease when cool. According to Anycubic, this glass bed has a microstructure with a high thermal expansion coefficient; meaning it will expand a lot when heated up, and shrink a lot when cooled down [117]. The idea is that the microstructure will shrink, and change faster than the 3D printed part, which makes the bottom layer break away from the glass surface.

#### Testing bed adhesion

A test was devised to compare bed adhesion properties of this new Ultrabase bed in comparison to Prusa's

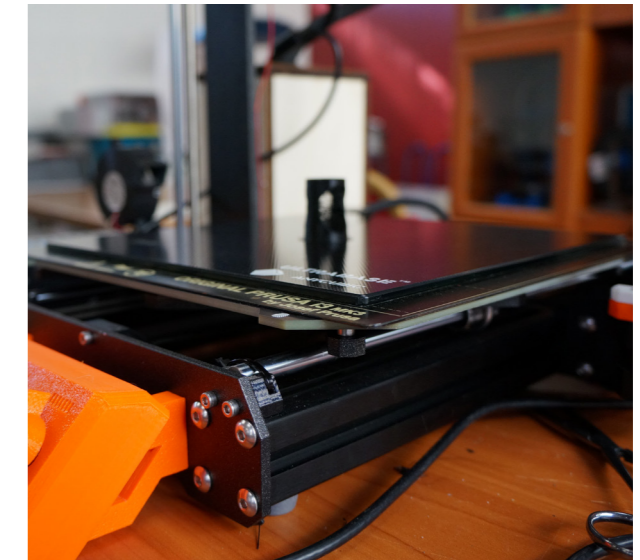


Figure 65: Showing the glass Ultrabase bed mounted on the Prusa

conventional PEI coated bed. A full report on this test can be found in appendix Q.

#### Results

During this test it was found that around 50 to 80+ N was needed to remove parts from the conventional bed, while the Ultrabase bed allowed parts to be removed with 2 to 45N. Moreover, dislodging forces decreased even further when the bed was actively cooled using fans. In this case it took an average of 17N to remove the parts, which is well below the maximum force of 28N that the motor can provide. Therefore:

**The best strategy for continuation is using the Ultrabase bed in combination with an active cooling system.**

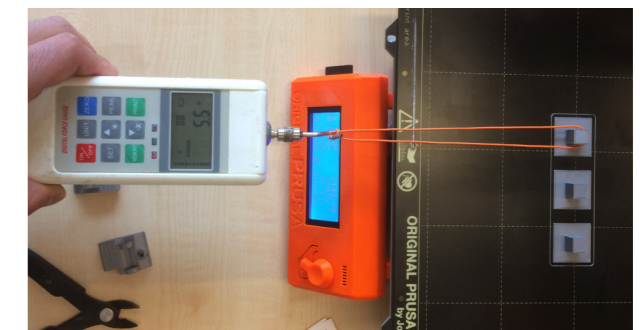


Figure 66: Setup of the bed adhesion test

### 5.4.4 Detailing

Now that the fundament of the solution was found, it was time to continue to focus on the details, such as designing the part removal mechanism and the active cooling system. Another change had to be made, since the original bed levelling probe of the Prusa printer did not work with the glass bed.

#### New bed levelling probe

The original Prusa PINDA probe works with induction, and can measure the steel bed from a distance of 2mm. However, the Ultrabase bed is 4mm thick, and therefore this setup does not work. A few different sensors were ordered and tested, and finally a sensor was found that was able to detect the metal through the glass sheet. After changing some code in the Marlin firmware, the printer was functional again, and could perform the bed levelling procedure with this new sensor. A new mount had to be designed on the extruder base. Two iterations were made of this part. The final setup is shown in figure 67.

#### Designing the part removal mechanism

Since parts were basically popping of the bed with this new technique, attempt 1 (using the aluminum wall), was given another go. This time it was successful in removing the part. This test was repeated 5 times with different size parts, and every time the wall proved sufficient in removing the part.

A mechanism was designed and built using the same aluminum wall, a 5V servo and a 3D printed frame mount. This servo was able to rotate the aluminum wall down and onto the bed. This way the whole process can be automated.

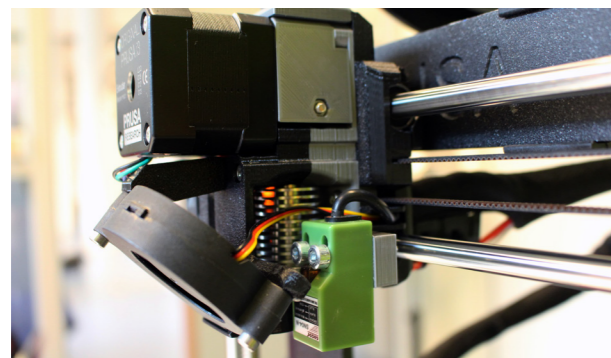


Figure 67: New bed levelling probe (green) mounted on the extruder

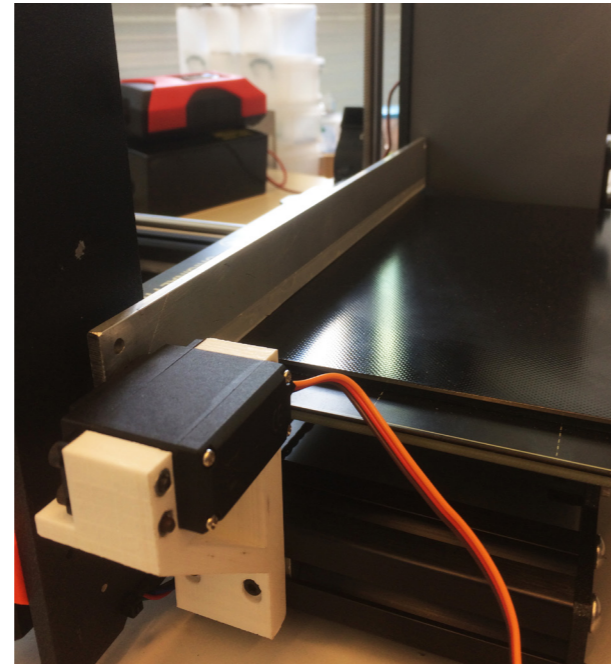


Figure 68: Showing first prototype of a wooden laser cut enclosure

#### Designing the active cooling system

The part dislodge test showed that cooling down the bed fast can greatly reduce the force required to dislodge the part. The added benefit is that the time required to cool the bed is greatly reduced, and thus uptime is improved.

Several strategies were devised for cooling the bed faster.

#### Attempt 1: Aluminum channel cooling system

One idea was to create aluminum channels, and force air through these to create an efficient cooling system. The idea was to place this system between the heating element, and the glass bed. It was hypothesized that during the

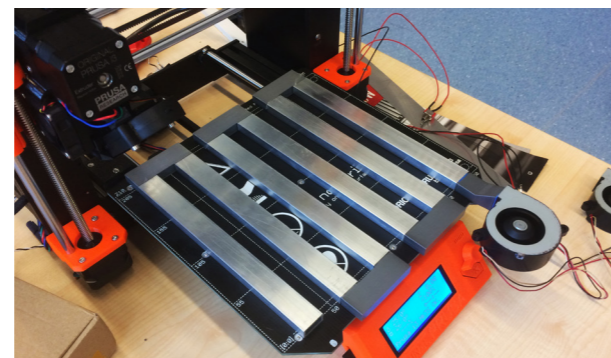


Figure 69: First attempt of an active cooling system using aluminum channels

heatup phase, the heat would be able to easily conduct through the aluminum material. During the cooldown phase, it was hypothesized that the forced airflow would quickly cool down the aluminum channels, and thus cool down the bed rapidly.

#### Result

Unfortunately this did not work as planned. The length of the channels was so long that the fan was not able to create an effective airflow. The time to cool down the bed with this system was approximately equal to letting the bed cool down naturally.

#### Attempt 2: Just fans

During preliminary experimentation it was found that blowing air directly onto the print bed with two projector fans was a very effective way to cool the bed. A test was devised to find the optimal placement for the two fans. Four different setups were tested:

1. Using no fans (passive cooling)
2. Fans placed under the bed
3. Fans placed on top of the bed
4. Fans placed on the sides of the bed

#### Result

For all of these setups, the time was measured to cool down the bed from 60 to 25 °C. It was found that cooling down the bed passively, without fans, took 27 minutes in the Netherlands, and 42 minutes in Kenya. Using fans on the side brought this time down to 8 and 15 minutes respectively. It was found that placing the fans on the side is the optimal setup to cool the bed down fastest. An extensive report on this test can be found in appendix R.

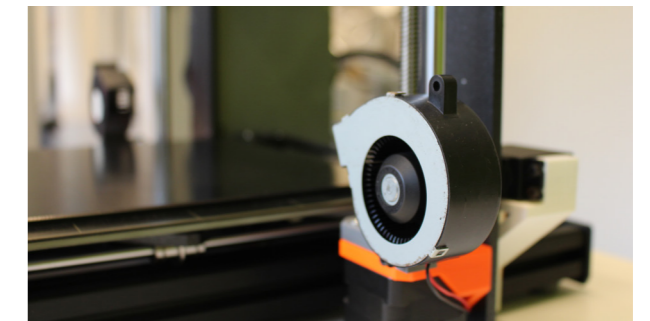


Figure 71: Setup of the most effective fan placement for active cooling

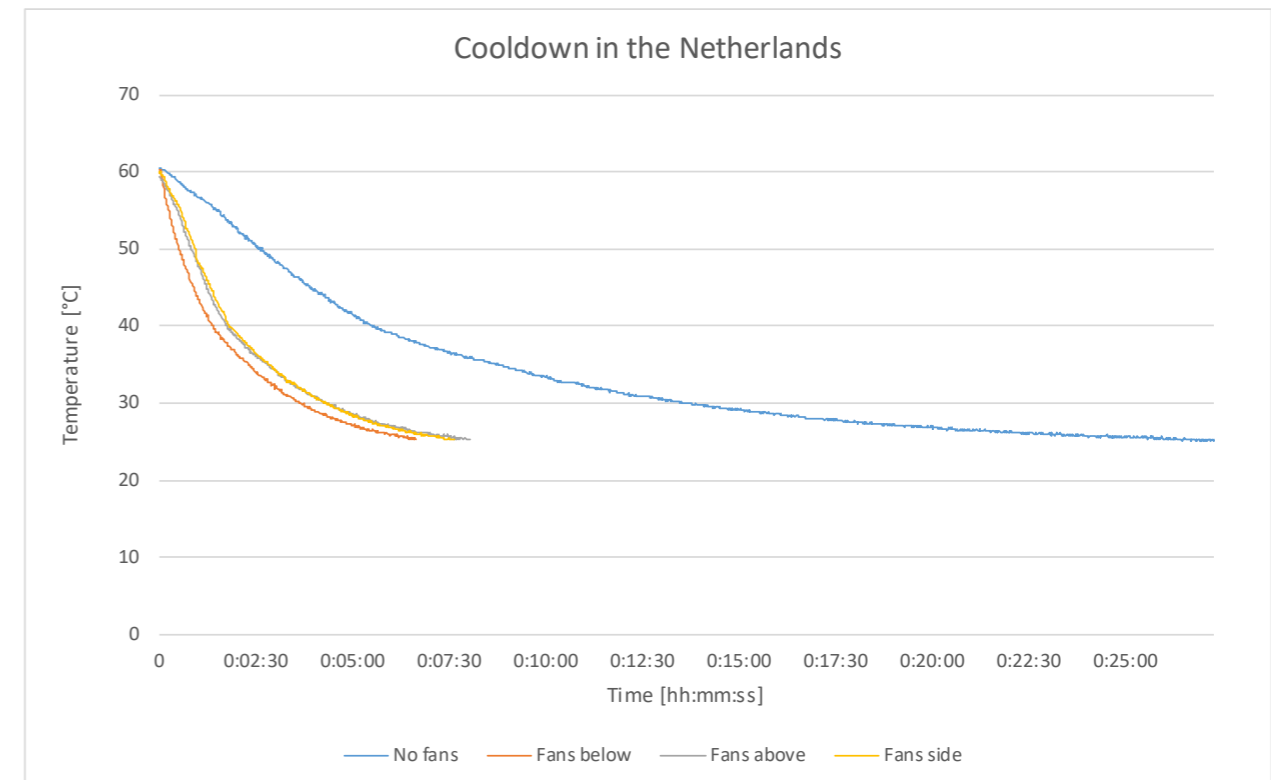


Figure 70: Showing results of a bed cooling test, where different placements of fans were tested to find the optimal setup

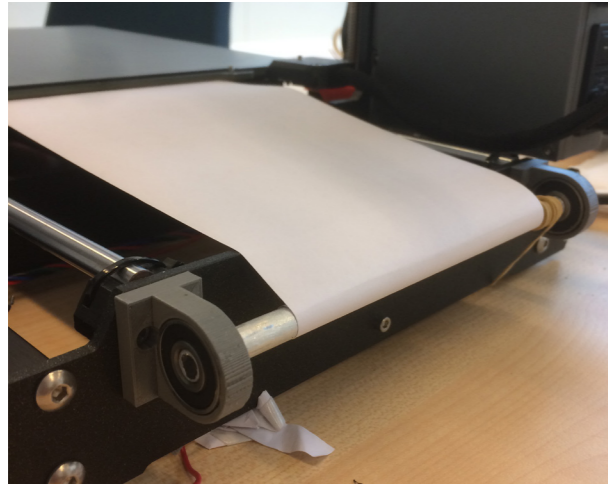


Figure 72: First prototype of the part catching system

### Part catching system

The system to remove the part from the print bed functions well. However, once the part is dislodged, there is no solution for moving it completely away from the printer. Therefore, a part catching system needs to be designed, that can catch the part once it falls off the bed, and can then eject it away from the printer.

A first prototype was built using a sheet of paper, a rubber band and an aluminum shaft extended between to bearings. This was a successful proof of concept, and it functioned well. Next this prototype was improved by switching to a more durable plastic material, and by using a spring mechanism for retraction, as shown in figure 73.

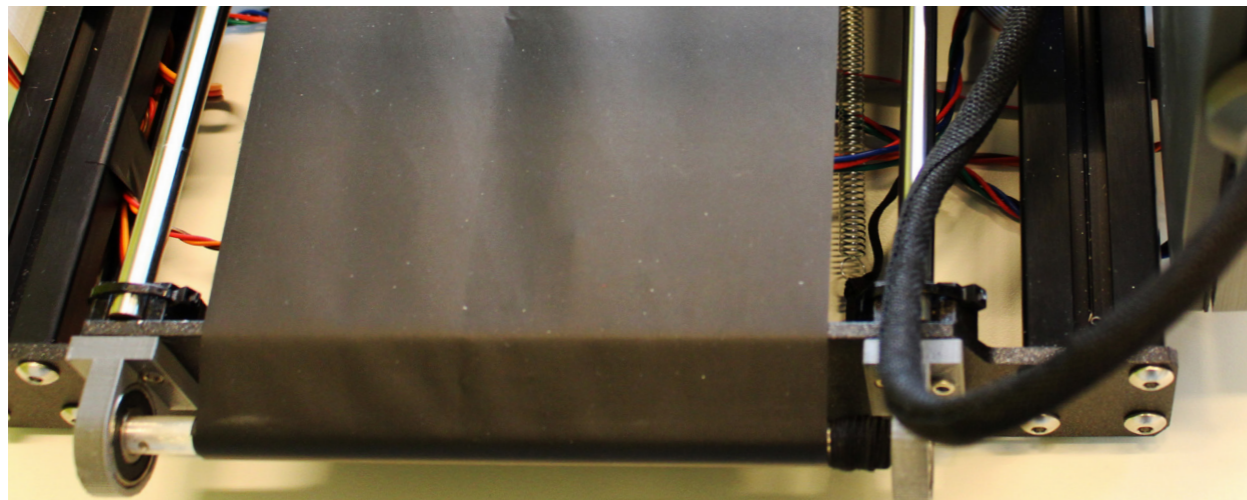


Figure 73: The final part catching system utilizes a spring mechanism to retract the plastic film

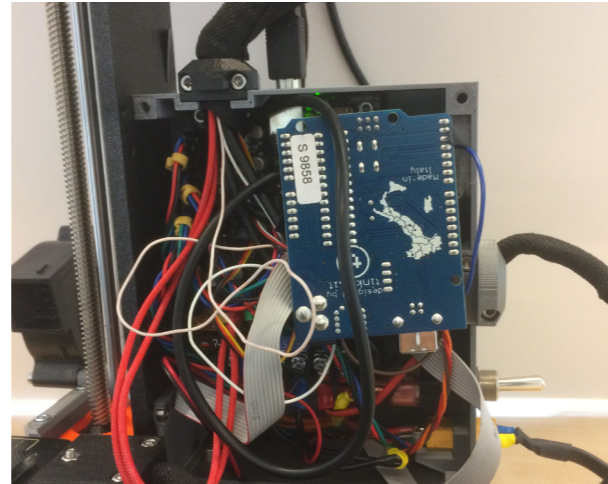


Figure 74: Placement of the arduino in the electronics enclosure; a tight fit

### Control and electronics

To control the movement of the part removal arm, an external controller had to be added, as the original Einsy board powering the printer did not have free pins for this job. An Arduino was added for this function. A free pin was found on the Einsy board that could be used to signal the Arduino to start the part removal procedure. The fans were powered using a simple switch, that could be toggled by moving the extruder gantry against it.

### Final test

A proof run of the entire system was performed. A simple finger cast was selected as a case product for printing. The procedure is as follows:

- Heating (2 min)
- Printing (15 min)
- Cooling (8 min)
- Part removal (20 sec)

The total production time per finger cast was therefore 25 minutes. The system was turned on and left alone for 2.5 hours. A time lapse of this process was recorded with a GoPro.

### Results

The system was able to autonomously produce 5 finger casts within this time, and performed as was expected. However, the fourth finger cast rolled of the part catching system, and got stuck between the bed and the frame. A recommendation will be given to solve this issue.

### Final design

The final design consists of the following elements:

- Part removal arm + 3D printed mount
- 12V Blower fans + 3D printed mounts
- Induction sensor
- 5V Servo motor

- Aluminum shaft
- 3D printed bearing holders
- Bearings
- Spring + elastic cord
- Thin plastic film

*Note: The Arduino and pushbutton are not included, as these were needed only for prototyping purposes.*

### Cost price

The final cost price is estimated at around \$30.

Part	Function	Sourcing	Cost
Aluminium rod	Part catching	Local	\$1.00
Aluminium arm	Part removal	Local	\$1.00
Servo motor	Part removal	Import	\$3.30
Plastic film	Part catching	Local	\$0.50
Spring	Part catching	Local	\$0.20
Blower fans 12V (2x)	Cooling	Local	\$5.00
3D printed parts	Mounts	Local	\$0.50
Bearings	Part catching	Local	\$2.00
Induction sensor	Bed levelling	Import	\$2.00
Ultrabase bed	Printer bed	Import	\$13.00
<b>Total</b>			<b>\$28.50</b>

Table 18: Cost estimation of the automatic part ejection system

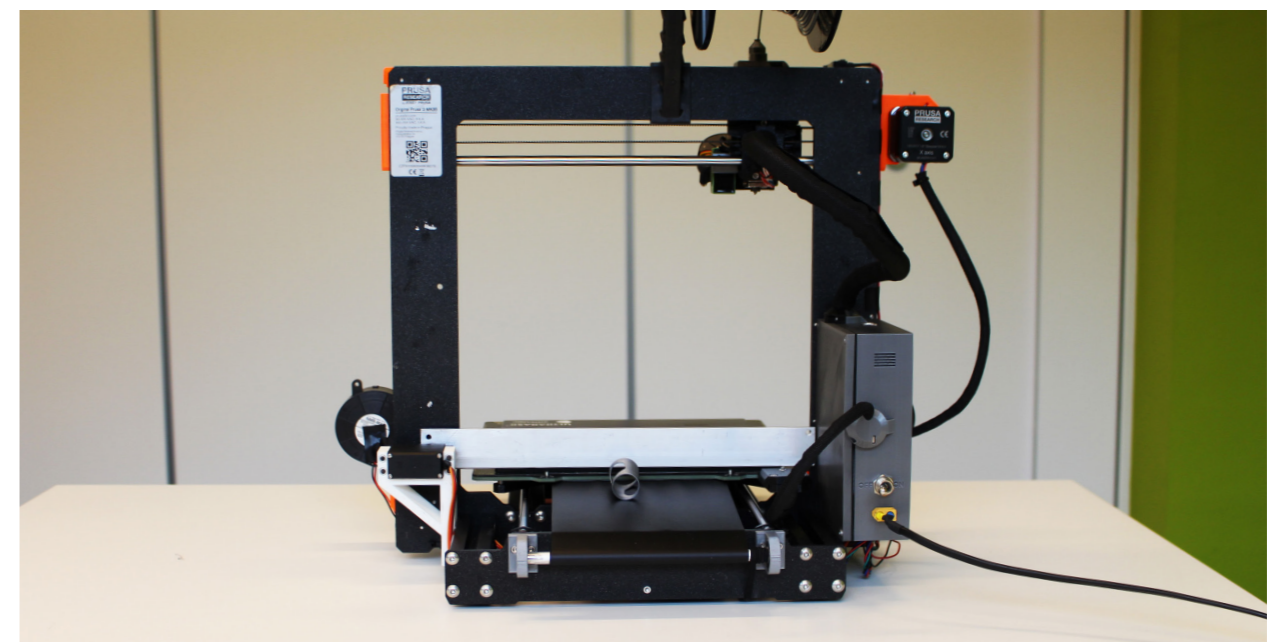


Figure 75: During the final demonstration test of the automatic part ejection system

## Chapter 5.5

## Connectivity and use

The printer should be useable by virtually anyone, without the need of a computer

To make an impact with 3D printing in Sub-Saharan Africa, it is of vital importance that the printer can be used by many people. Solutions for this challenge are explored only on a conceptual level.

### Requirements

- Hospitals should be able to order parts
- 3D printer operator should be able to receive orders
- 3D printer operator should be able to send print files to the printer
- 3D printer operator should be able to view printer status, health and maintenance notifications

Currently most, if not all, desktop 3D printers are designed to be used with an SD card. The user will load the print files from his computer on an SD, and afterwards plug this into the 3D printer. The 3D printer can then run the print directly from the SD. However, the goal of this project is to make the printer useable without the need of a computer, so a different solution needs to be found. The operator will need to be able to send files to the printer, as well as view current printer status and settings. Moreover, the hospitals need to be able to order the parts they require, even when they do not have access to a computer.

### The smartphone app

During the field trip several discussions with Ben and others from the Kijenzi team led to hypothesis that it would be best to develop an app that can be used by both stakeholders. Since almost all Kenyan's own a smartphone with internet, the hospital personnel can use the app to order parts from an online catalogue. This order will then arrive at the nearest 3D printer operator, who can start printing the order. The Kijenzi team is already working on such a system. In this case a solution still needs to be found for how the operator can use the printer.

### Control without computer

Two solutions were devised for the operator to use the printer:

1. The printer has an onboard control panel, and received orders through WiFi or 4G
2. Orders are pushed from smartphone to printer through Bluetooth

### Onboard control panel

By supplying the printer with an onboard control panel, all functions can be handled by the printer itself. This solution will allow the printer to become centralized, and will allow it to be run without the aid of any external devices like a smartphone or computer. This function will require to have many native smartphone features built into the design. Therefore it will need a microcomputer, such as a Raspberry Pi, together with a touchscreen panel, and a WiFi or 4G module.

### Cost

A sim module costs around \$ 4 [119], and 2GB of data can be purchased for \$ 5 per month from Safaricom [120]. The Raspberry Pi and touchscreen can be acquired from AliExpress for around \$ 100 excluding shipping [121, 122]. This increases the cost of the printer with around \$ 105, plus \$ 5 monthly subscription fees.

### Smartphone

It is also possible to operate the printer with a smartphone via Bluetooth. This has been previously done in the Kijenzi printer, designed for Kenya [10]. The operator will have the app running on his smartphone. When he receives an order on the app, he can then push the required print files to the printer through Bluetooth. Printer status, health and maintenance advise can then also be viewed on the app.

### Cost

This feature will only require the addition of a HC-05 Bluetooth module, which costs around \$2.50 excluding shipping from AliExpress [118].

## Use case 1: Onboard control panel

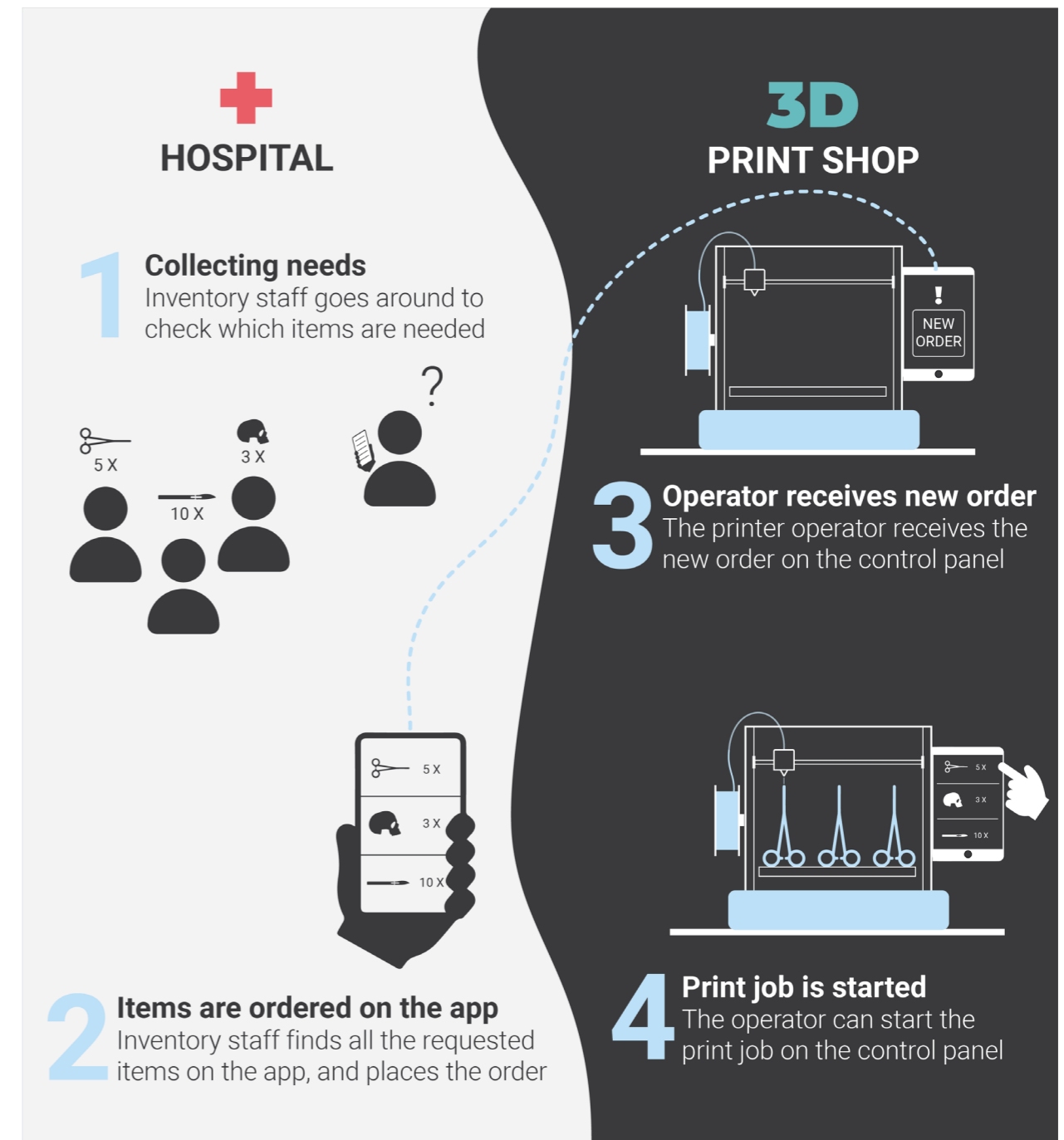


Figure 76: Use case 1, controlling the printer with an onboard control panel

## Use case 2: Smartphone

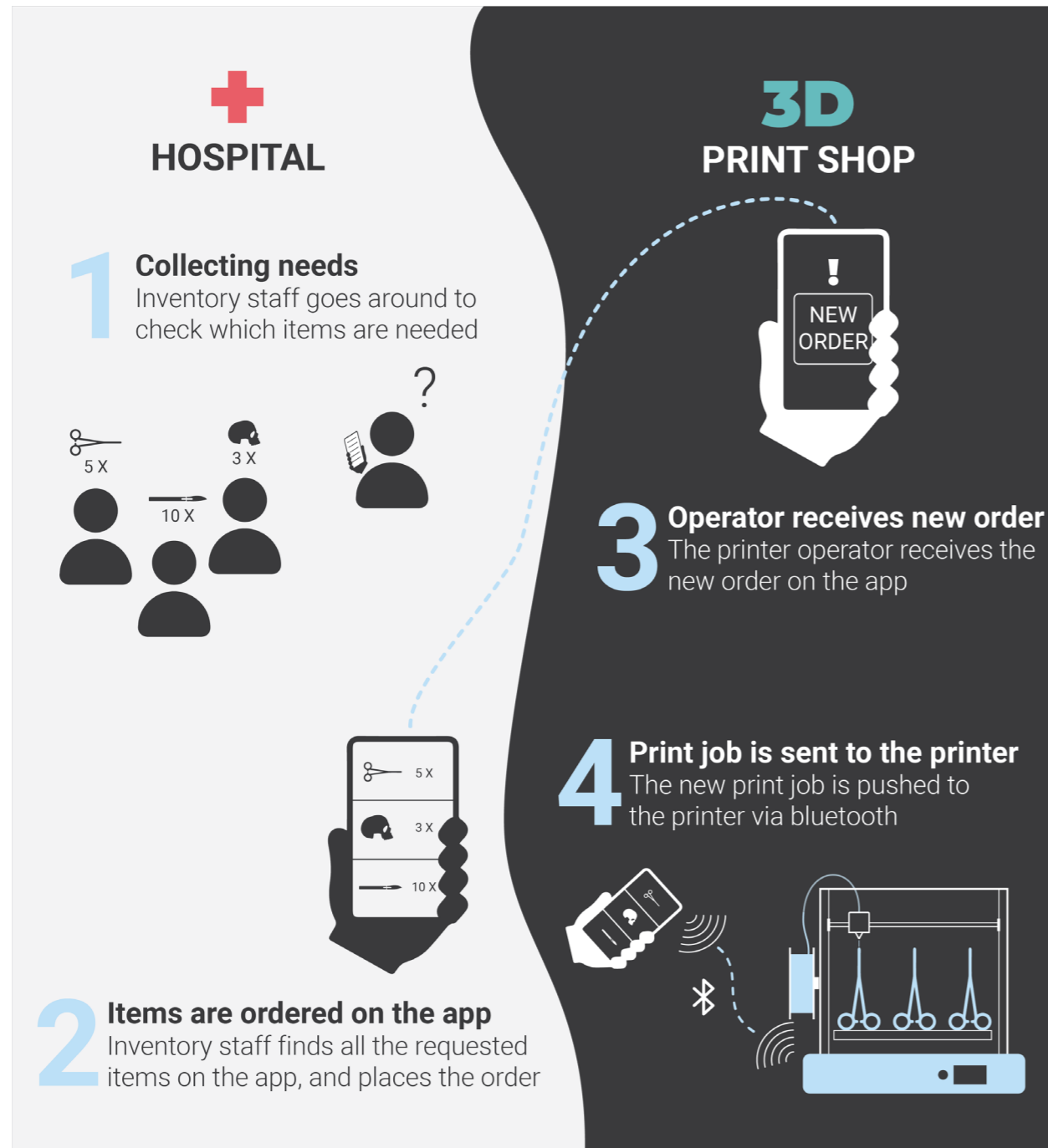


Figure 77: Use case 2, controlling the printer from a smartphone

## Evaluation

### Onboard control panel

This turns the printer into a standalone solution that can be used without any external means. However the costs will be high, starting around \$100 for the screen, and adding at least \$5 a month for internet subscription costs.

### Smartphone

Using the printer with a smartphone is by far the cheapest option, as it will only require a \$1.5 Bluetooth module. The downside to this method is that it will force the user to own and use a smartphone for operating the printer.

### Conclusion

Although the Bluetooth solution will require the operator to own and use a smartphone for operating the printer, it does come at a huge cost benefit of \$100. This is considered a major drawback of the onboard control panel, and in conflict with the design driver "Design for affordability". The Bluetooth solution is considered most appropriate for the context.

### Cost

The total cost for this solution is estimated at \$2.50.

Part	Function	Sourcing	Cost
HC-05 Module	Bluetooth	Import	\$2.50
<b>Total</b>			<b>\$2.50</b>

Table 19: Cost estimation of the connectivity solution

*Note: The solution proposed in this chapter has not been tested or validated, due to limited resources. Moreover, this chapter did not address printer operation and maintenance. A recommendation for further research and development can be found in chapter 7.3, page 108.*

## Chapter 5.6

# Transportability

The printer should be compactly transportable in a partly assembled state

*The goal of this chapter is to find a state of disassembly from where the printer can be quickly reassembled, while still allowing it to be compactly and safely packed for transport. This will be developed on a conceptual level.*

### Requirements

- During delivery to the customer, the printer should be compactly and safely transportable
- The printer should be delivered partly assembled

During the analysis it was found that the 3D printer should be delivered partly assembled to the customer. Interviews in Nairobi showed that users want to assemble the printer themselves in order to get a thorough understanding of the functioning of the machine. The original Prusa is delivered

completely disassembled, which is why it takes an average user 7 to 9 hours to assemble it (it took the author around 8 hours spread over two days). This process is considered too time intensive and difficult to match the context of Kenya. Therefore, a balance should be found between the least amount of assembly required, while still allowing the printer to be compactly and safely packed for transport.

### Finding the perfect state of disassembly

The printer was disassembled piece by piece, and along the way different setups of packing were tried out. Whenever it was concluded that parts could still be easily damaged during transport, the disassembly would continue, and new experiments were conducted. This process was repeated until finally a setup was found in which many parts of the printer are still assembled, while the entire package can be safely and compactly packed. This is shown in the final two figures.

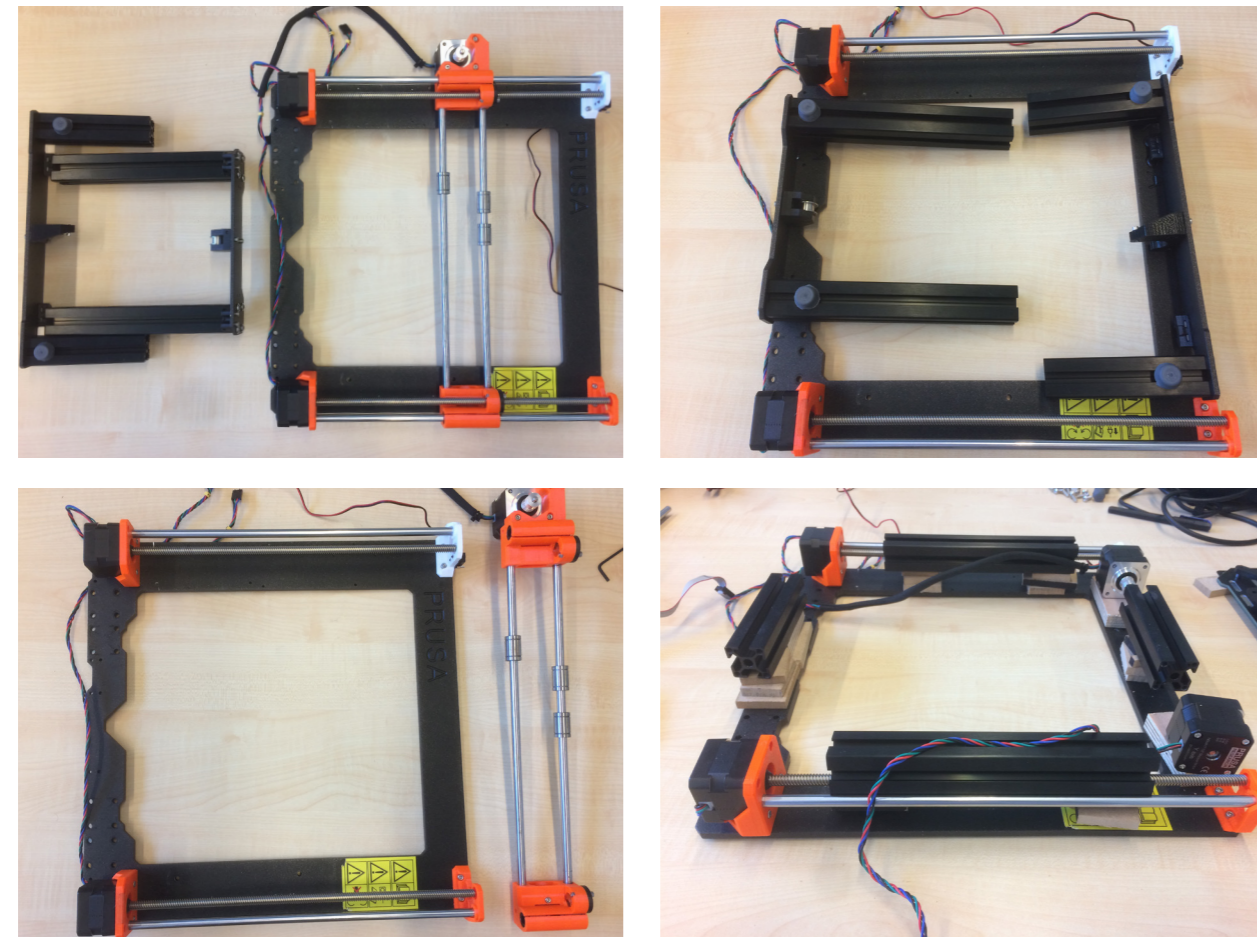


Figure 78: Showing different states of disassemblies in different orientations, with the goal of finding a safe and compact way of transportation

### Final result

The final result was found halfway along disassembling the printer. In this setup it is possible to use the frame parts as structural support for the entire structure. This way, sensitive parts like lead screws and smooth rods will be protected, as any forces from the top, bottom or sides will be applied to frame parts that can handle the load. As shown in the figure, pieces of wood were put under the frame parts to make sure that all elements are level, and higher than the sensitive parts.

- Size of final package: 38x38x6 cm
- Can be assembled in 1-2 hours

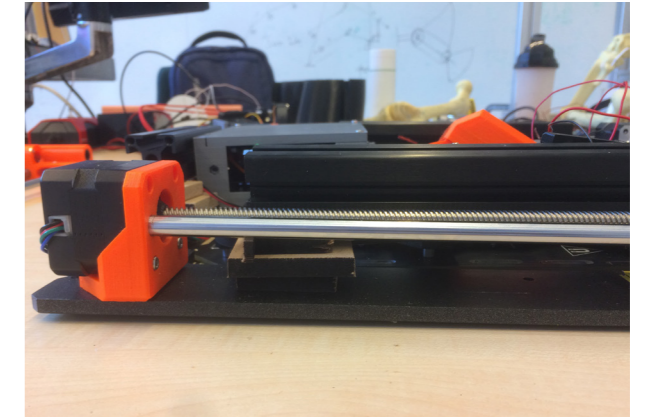


Figure 79: Rugged frame parts provide structure and keep fragile parts safe

*Note: The final result of this chapter is still on a very conceptual level and will require more work and testing to become a viable solution. Moreover, this chapter did not address transportability once the printer has been assembled. Recommendations are provided in chapter 7.3, page 108.*

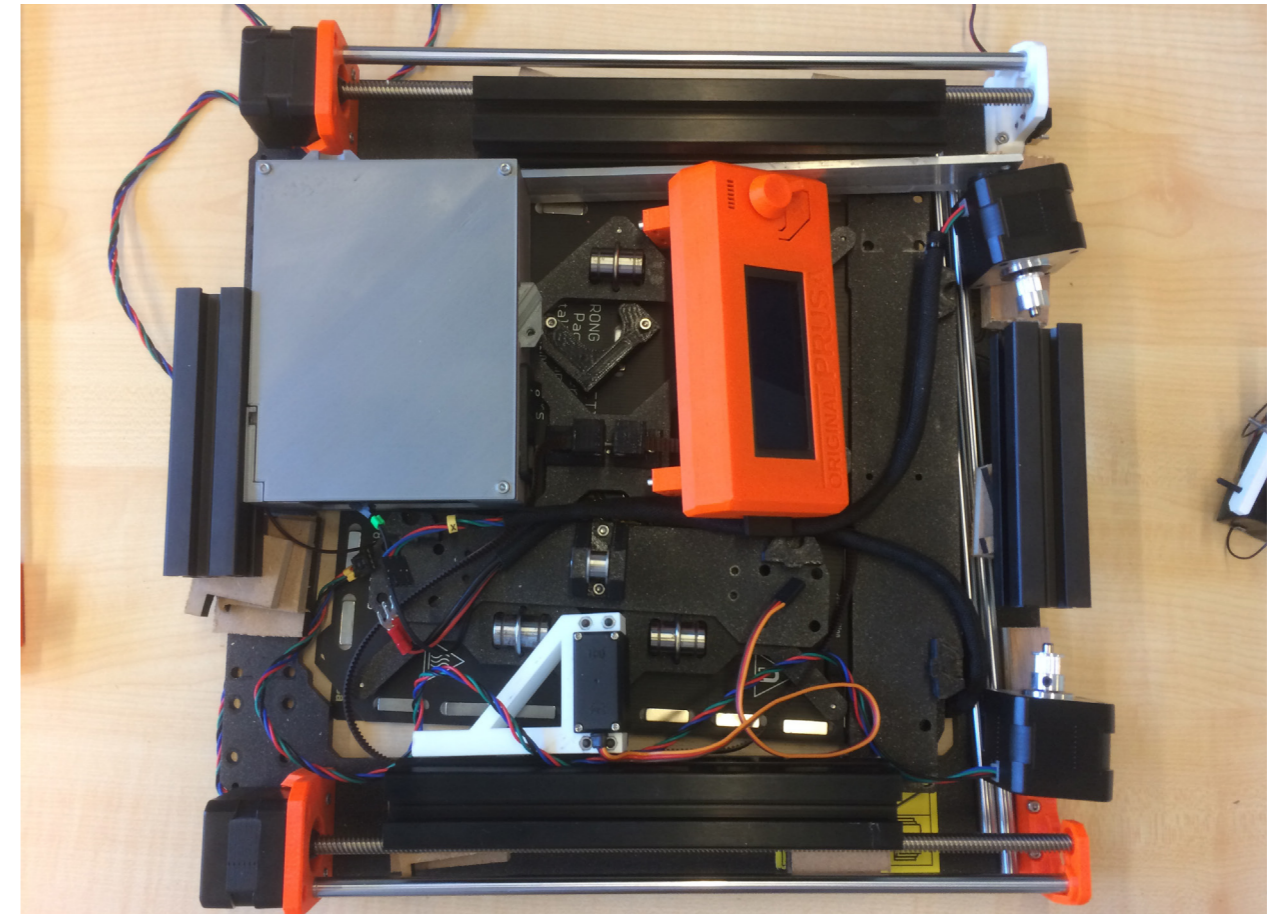
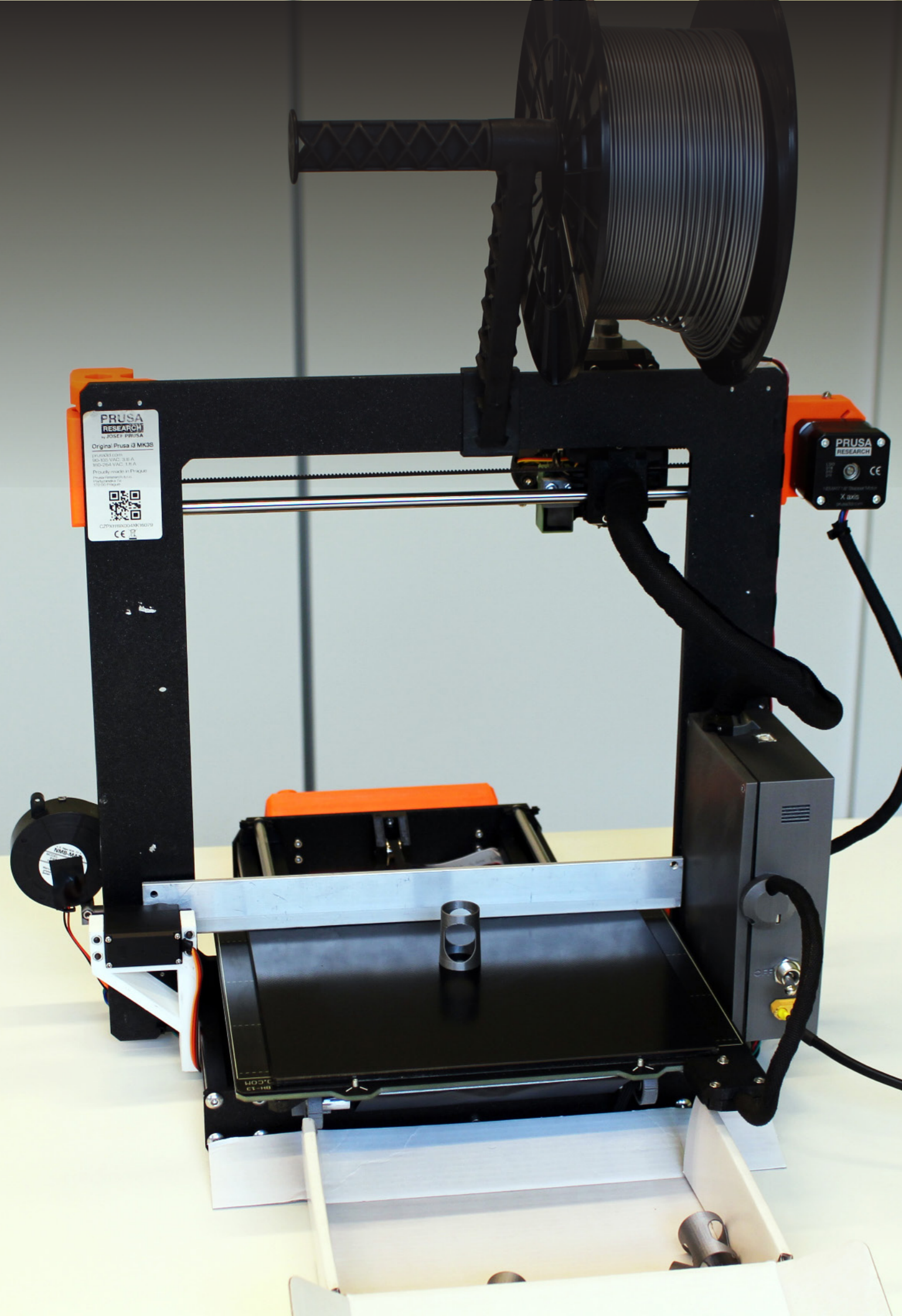


Figure 80: The final result is a partly assembled state where the outer walls consist of rugged frame elements that provide structure and protection



## Chapter 6

# Final design

The design phase has resulted in the development of solutions for all the design challenges. All of these solutions come together in the final design proposal of a 3D printer for healthcare in low resource settings. In this chapter the final design is described along with its features, specifications and cost price.



## Chapter 6.1

# Overview

A set of renders provides a visual overview of the final design.

Figure 81: Render showing front view of the final design

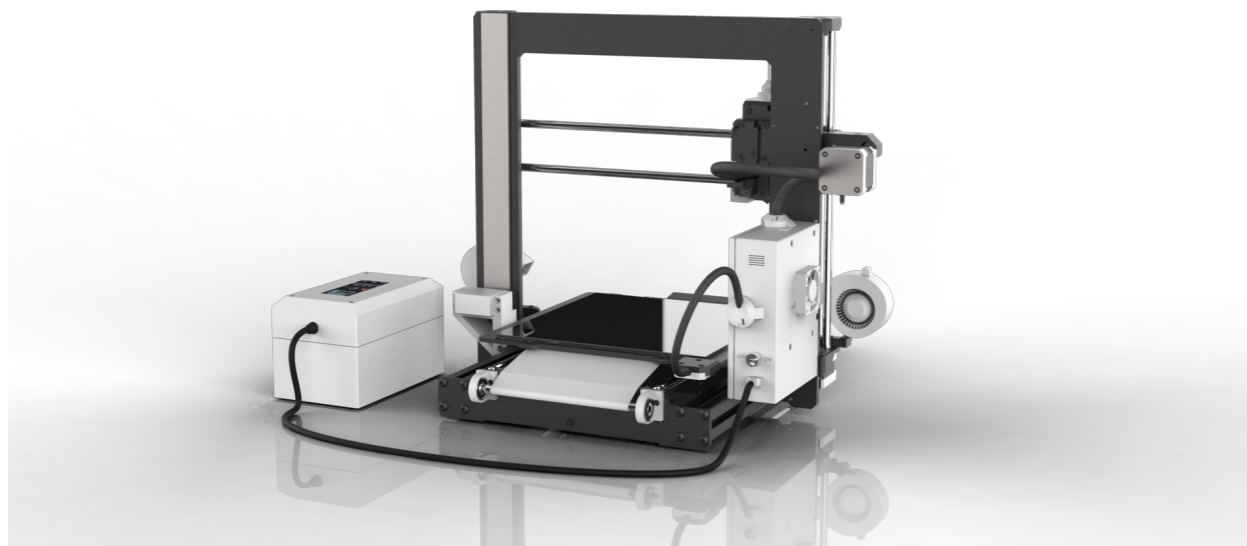
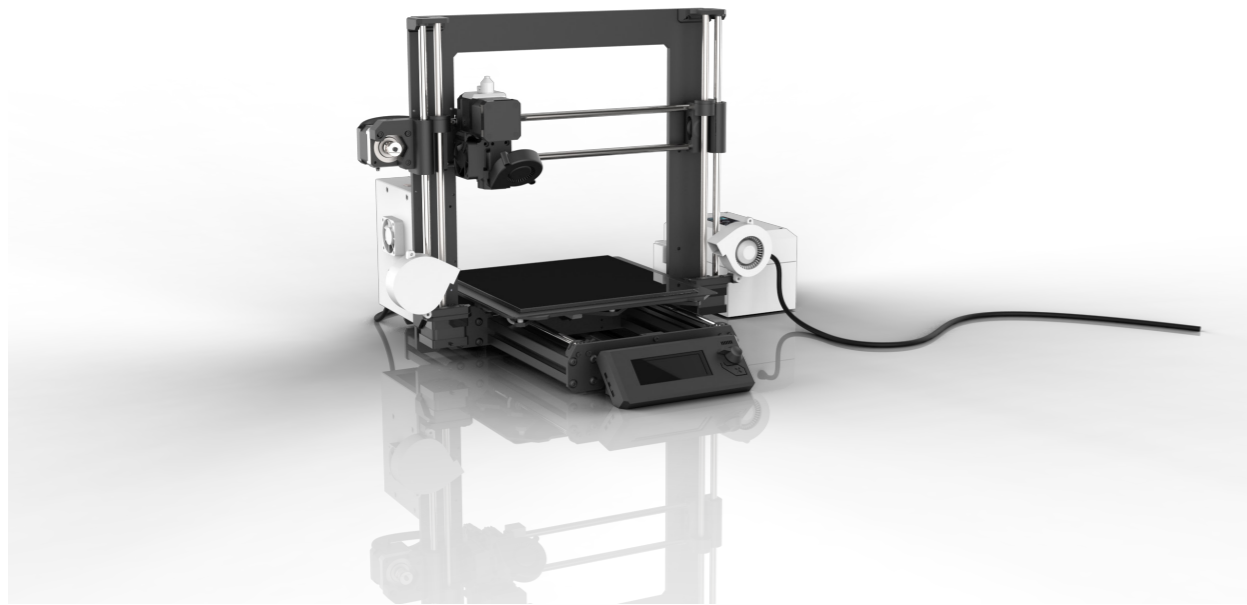
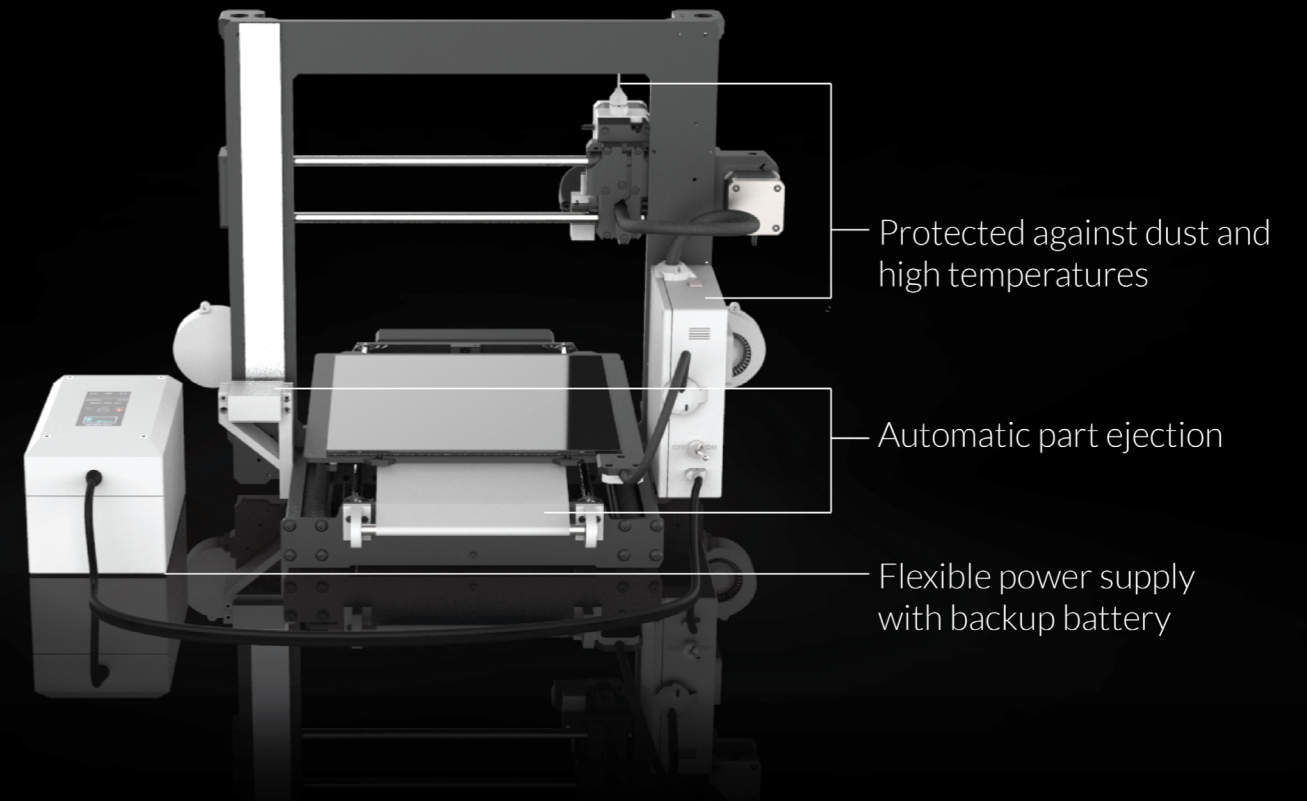







Figure 82: Render showing rear view of the final design

# MUUMBA

3D printer designed for healthcare in Sub Saharan Africa



-  Can deal with power outages and surges
-  Protected against dust and high temperatures
-  Able to print continuously
-  Easy to use by anyone with a smartphone
-  Compact for transport, quick to assemble

## Chapter 6.2

# Features

In this chapter the final design is described through its unique features.

The final design features a flexible power supply with backup battery, protection against dust and high temperatures, an automatic part ejection system, easy use through smartphone and lastly it is compact to transport, and quick to assemble.

### Flexible power supply with backup battery

To be able to deal with frequent power outages and power surges, a new type of power supply had to be designed. The final solution is a smart charger combined with a 12V 7Ah sealed lead acid battery (VLRA). The charger and battery are connected in parallel to the printer, and will also supply the printer with enough power. In case of an outage, the battery can continue to supply the printer with power for approximately 30 minutes. After the battery has been drained below a critical point, a safety circuit shuts off power to the printer. In this case, the active print can still be resumed using Power-Loss recovery.

#### Specifications

- Can power the printer off-the-grid for ~30 minutes
- Flexibly carriable, just like a laptop charger
- Estimated battery lifetime of 5 years
- Costs \$45

### Filament dust filter

Filament is known to collect dust over time, and this can enter the extruder and cause nozzle clogs. To prevent this issue, a simple dust filter has been designed that utilizes a piece of foam to wipe off any dust stuck to the filament.

#### Specifications

- Uses a dust filter that can be easily replaced
- Costs \$1.5

### Dust proof electronics enclosure

To prevent dust from accumulating on the controller board, and to provide adequate cooling, a new enclosure has been designed and prototyped. The enclosure is tightly sealed with foam padding around cables and a rubber seal between the removable lid and the enclosure, providing it with an IP5 rating. A fan with dust filter ensures proper ventilation, and the power supply can be easily plugged in with an XT60 plug. The removable door provides easy access to the electronics.

#### Specifications

- Tightly sealed from dust (according to IP5)
- Effective cooling of the electronics
- Allows for easy power supply plug-in
- Removable door for easy cable access
- Costs \$7

### Automatic part ejection system

To ensure that the printer has a maximum uptime, an automatic part ejection system has been developed. This allows the printer to produce parts continuously, and partly autonomously. The system is comprised of four important elements. The Ultrabase glass bed ensures that parts break off the bed when the bed is cooled down rapidly. This cooling is facilitated by two blower fans attached to the sides. Next the part removal arm can go down, and the printed part is pushed against the arm by movement of the bed. This way the part ends up on the part catching system, which is used to move the part away from the printer.

#### Specifications

- Ejects parts automatically once the printing has finished
- Allows for continuous production, and enables a print queue to be setup
- Can double the profits for a 3D printer business owner
- Costs \$30

### Easy to use with a smartphone

The printer can be easily used with a smartphone, through Bluetooth. An app allows the operator to access an online catalogue of parts, receive print orders, send print jobs to the printer, and view printer status and maintenance requirements.

#### Specifications

- Costs \$2.5

### Compact for transport, quick to assemble

The printer can be compactly transported in a partly assembled state to the end user. The structural frame elements are used to provide structure during transport, so there is no risk of damaging components. Upon delivery, the user is able to assemble the printer within one to two hours.

#### Specifications

- Compact package size: 38x38x6 cm
- Can be assembled in 1-2 hours



Figure 83: Flexible power supply with backup battery

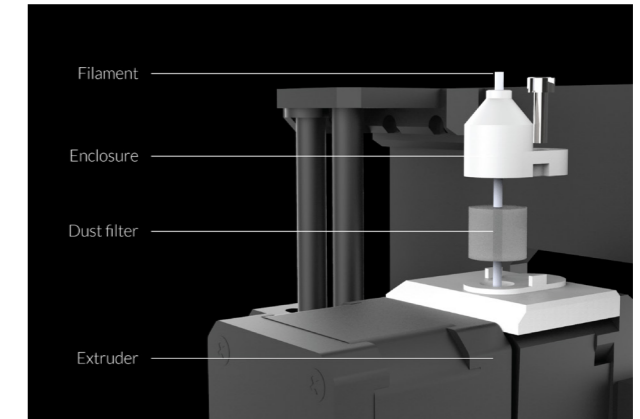


Figure 84: Dust filter

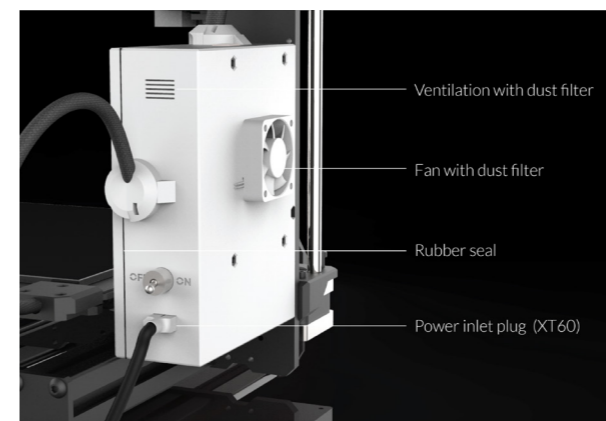


Figure 85: Dust proof electronics enclosure

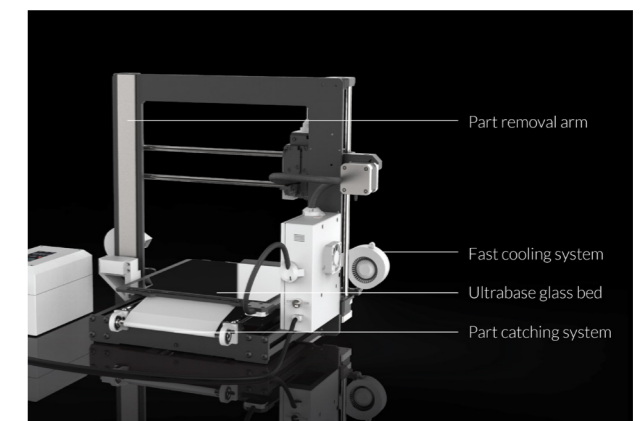
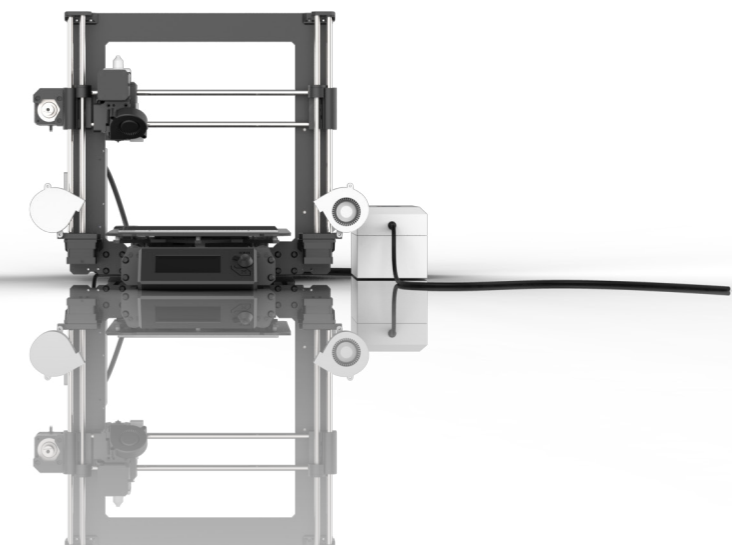


Figure 86: Automatic part ejection system



## Chapter 6.3

# Specifications and costs

The final design is described through its specifications, and a cost estimation is provided.

## Specifications

The final design can be described with the following list of specifications:

- Frame type: Cartesian
- Extruder type: Direct extruder for 1.75mm filament
- Supported materials: PLA, ABS, PET, PETG, TPU (and more)
- Build volume: 10.000cm<sup>3</sup>
- Build envelope: 200x200x250mm
- Heated bed
- Automatic mesh bed levelling
- Connectivity through smartphone or SD card
- Shipping packacke size: 38x38x6 cm
- Assembly time: ~1 hour
- Power: 220-240V AC, 12V DC
- Surge protection
- Off-the-grid run time: ~30 minutes
- Automatic part ejection system with fast bed cooling
- Estimated cost price: \$ 330
- Weight: 9.2 kg

## Cost estimation

The material cost of the 3D printer was estimated based on suppliers found on AliExpress, as well as prices of locally sourced items, as provided by Karl [42]. Based on Karls price indications, it is estimated that motors; fans and hardware, such as bolts and nuts, can be sourced locally in Nairobi for \$ 18. The steel sheets for the frame are also locally procurable for \$ 30. The same items shipped from AliExpress would cost respectively \$ 48 and \$ 40. Shipping and tax has been roughly estimated to be ~\$ 50.

Two cost price estimations are put together:

### 1. Costs of the Prusa without upgrades

The total cost is estimated at \$ 330, including tax and shipping. The simplified cost breakdown is shown in table 20.

Part	Cost
Electronics	\$ 90
Power supply	\$ 25
Extruder	\$ 35
Linear guidance	\$ 50
Frame	\$ 80
Shipping and tax	\$ 50
<b>Total</b>	<b>\$ 330</b>

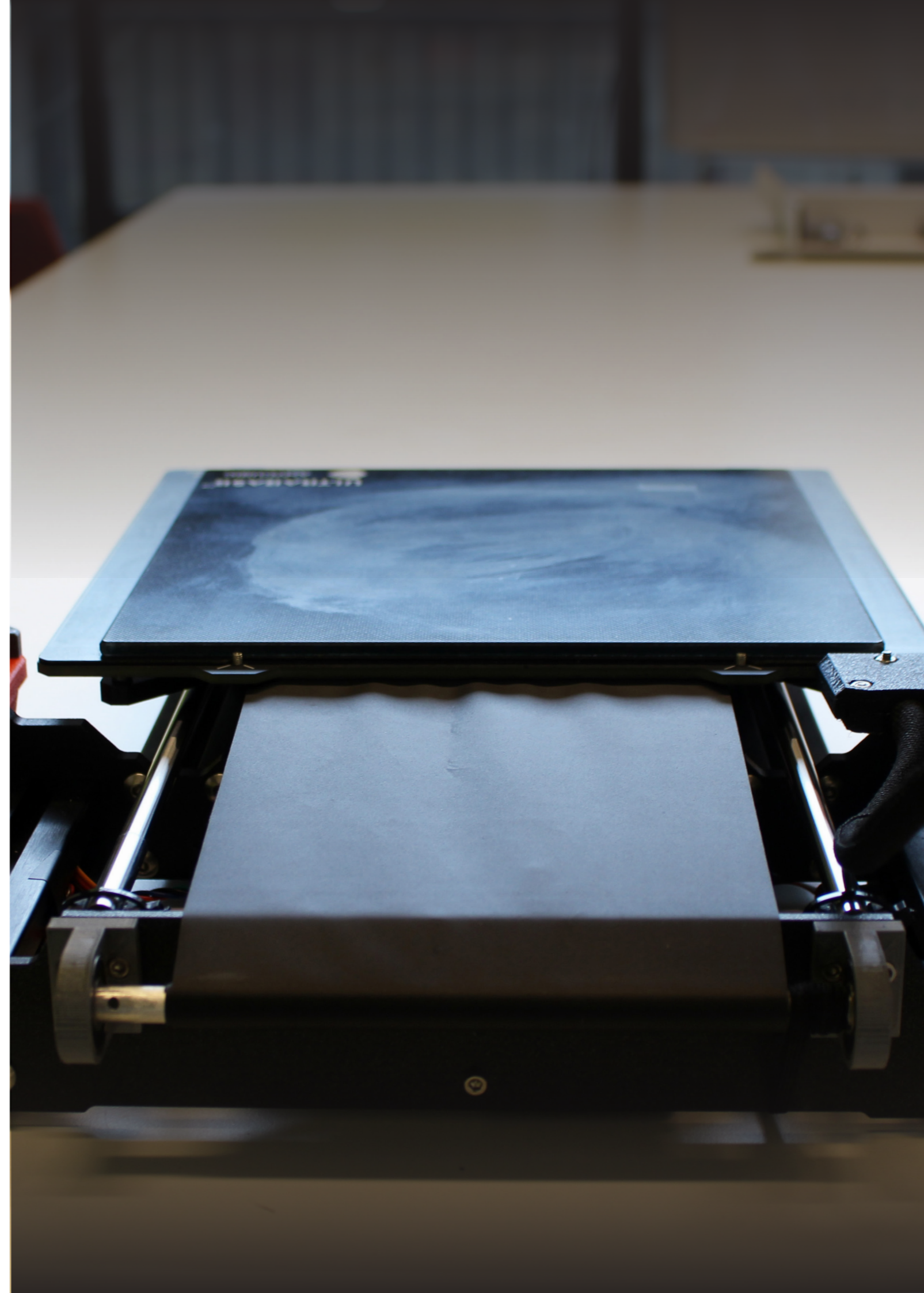
Table 20: Cost estimation of the Prusa i3 without upgrades

### 2. Costs of the Prusa with upgrades

The upgrades add a cost of \$ 42.50, making the total cost \$ 372.50. This is shown in table 21.

Part	Cost
Electronics	\$73.00
Extruder	\$35.00
Linear guidance	\$50.00
Frame	\$80.00
Power supply	\$45.00
Dust filter	\$1.50
Electronics enclosure	\$7.00
Part removal system	\$28.50
Connectivity	\$2.50
Shipping and tax	\$50.00
<b>Total</b>	<b>\$372.50</b>

Table 21: Cost estimation of the Prusa i3 with upgrades (the final design)





“It’s  
pretty hot”  
Thermal Gun

## Chapter 7

# Conclusion

This thesis is concluded with an evaluation of the final design by a panel of carefully selected experts. Besides this expert evaluation, the design is also evaluated based on the list of requirements.

Next several recommendations are provided for continuation on the path of designing a 3D printer for healthcare in Sub-Saharan Africa.

The chapter closes with a reflection, looking back at the process and experience of the entire project.

## Chapter 7.1

# Evaluation

This project is concluded with an evaluation of the final design. To get an objective by carefully selected experts in the field.

### 7.1.1 Expert evaluation

#### Method

The final design was summarized in a short 15 page document, similar to the final design chapter in this report. Included in the document were an introduction, the design challenges and design drivers and lastly the final design, described through its features, specifications and cost price, with supporting images and visuals.

To accommodate this document, an evaluation questionnaire was created using Google Forms. The questionnaire contained multiple choice questions, based on a Likert scale answering system [123], as well as open answer questions. The complete questionnaire can be found in Appendix S.

For the evaluation a total of five (male) experts were carefully selected because of their relevance in the field of 3D printing for healthcare in low resource settings. All of the experts below have an abundant experience with 3D printing in Kenya, and the last two experts also have extensive knowledge and experience of 3D printing for healthcare in this context:

1. Derrick Mugasia [124], director of the MakerSpace, University of Nairobi
2. Karl Heinz [125], co-founder of Nairobi based 3D printing startup AB3D
3. Ishmael Mwangi [126], works at MakerSpace with Derrick, and designed and built a 3D printer
4. Ben Savonen [127], PhD graduate at Penn State University, and co-founder of Kijenzi
5. Tobias Mahan [128], PhD candidate at Penn State University, and co-designer of the Kijenzi printer

With Derrick Mugasia and Ben Savonen, an extra skype interview was conducted to discuss their responses to the questionnaire.

#### Results

A quick summary of the most important insights and findings from the questionnaire are shown below. A detailed overview of the results can be found in Appendix S.

##### General

- The found design challenges were considered complete and adequate
- It was generally considered that the design drivers form a fitting design strategy
- The list of requirements was considered adequate, but not complete; falling short on describing healthcare specific requirements as well as requirements on safety
- The experts all agreed that the estimated cost price is a well fit to the context, or could even be a little higher
- It was generally found that the Prusa i3 design was a good foundation for a 3D printer in this setting

##### Flexible power supply with backup battery

- It was found that this solution is feasible, adequately tackles the challenge and properly addresses values and needs of the context and user
- Rated by everyone as a very important solution

##### Dust filter

- Besides Tobias, everyone rated this solution very high in all fields

##### Electronics enclosure

- All experts considered the solution very important and feasible
- The experts all found that the solution addresses the values and needs of the context and user very well

*"Great solution to protecting the electronics!" - Ben*

##### Continuous printing

- The solution was rated slightly lower than the previous solutions
- Several experts had some concerns with the feasibility of this solution
- It was still considered an important solution

*"At Kijenzi we want to work with presliced 3D print files. However, this does not work in batch printing. Your solution solves this problem!" - Ben*

##### Connectivity and use

- This area is considered very important by all experts
- Ben and Tobias indicated that more work needs to be done in this challenge area

*"Discover the level of technical proficiency with various smartphone based applications to determine the allowable complexity for the app. Discover the level of proficiency in repairing complex mechanical systems to create a printer which is easily serviceable." - Tobias*

##### Transportability

- This area received a slightly lower rating compared to the other areas
- The challenge was considered fairly important
- The solution was found not to address the values and needs of the context and user very well
- Tobias indicated that the actual packaging was not addressed

*"Partial disassembly is a good preliminary solution to this challenge (and its the one our team used as well). I think an ideal solution would go a step further and allow a printer to be collapsed without being disassembled (as disassembly and reassembly can eventually start hurting print quality and consistence over time, even with auto calibration)." - Ben*

##### Overall

- The experts considered the final design to fit the context and user very well
- The experts rated the fit of the final design to the intended usage (producing medical equipment) slightly lower
- The final design was considered to be a better solution than what is currently available in the market

*"Quality assurance and control, use of 3D printed objects in medical context, scheduling maintenance/ upgrades" - Tobias*

*"I think more could be done to tailor this to the specific needs of manufacturing medical equipment and maintaining quality while doing so. I do not think that was a necessary feature for the first prototype, however, and this just represents an opportunity for future work. Overall, great job!" - Ben*

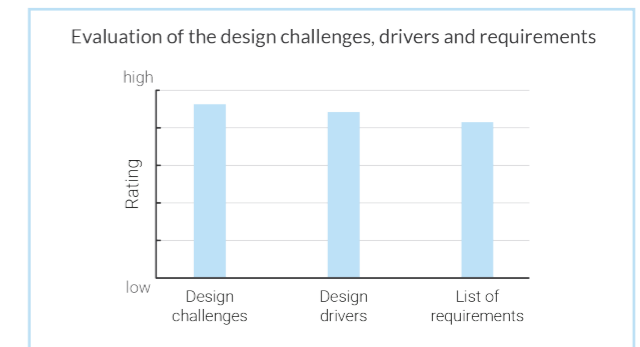


Figure 87: Evaluation results of the design challenges, drivers and requirements

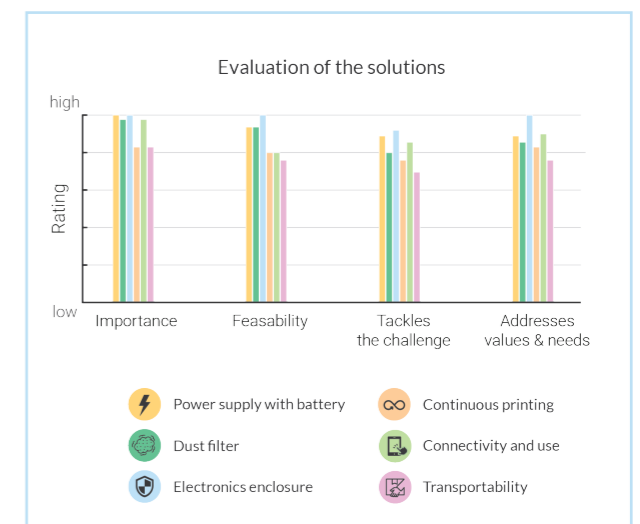


Figure 88: Summary of evaluation results of the different solutions

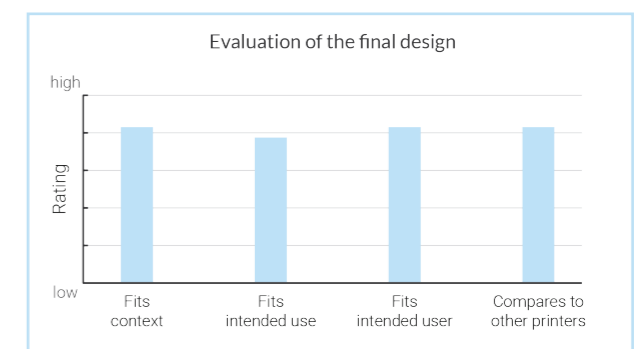


Figure 89: Evaluation of the final design

## 7.1.2 Evaluation of requirements

The final design is evaluated based on the requirements that were setup during the Synthesis phase.

### How to read

- ✓ Requirement was satisfied
- ✗ Requirement was not satisfied
- ❖ Requirement was nearly satisfied; more work is needed

### Updated list of requirements

This list of requirements was setup at the start of the design phase, and was slightly updated along the way. However, with the insights gained from the design phase, as well as the expert evaluation, a new more appropriate list of requirements was developed. This final list of requirements can be found in Appendix T.

### Evaluated list of requirements

- ✓ The printer should be able to produce parts with a maximum tolerance of  $\pm 0.5\text{mm}$
- ✓ The printer should be able to print with a minimum layer height of  $0.1\text{mm}$
- ✓ The printer should have a build envelope of  $200 \times 200 \times 200\text{ mm}$
- ✓ The printer should be able to print with  $1.75\text{mm}$  filament
- ✓ The printer should be able to print with at least: PLA, ABS, PET, PETG and TPU
- ✗ The printer should include a dehumidifying solution for the filament
- ✓ The selling price of the printer should not exceed \$ 800
- ✓ The production price of the printer should not exceed \$ 400
- ❖ The printer should be able to run and be setup with a smartphone
- ✗ The printer should be easy to use by anyone with minimal instructions
- ✓ The printer should be accompanied by a clear step-by-step instruction manual
- ❖ The printer should be made from, as much as possible, locally available parts and materials
- ❖ Parts that need common maintenance or replacement should be easily reachable
- ❖ The printer should be repairable with mostly generic and locally available parts
- ✓ The extruder should include a dust filter to prevent dust from entering the nozzle
- ✓ The printer should be able to blow off dust from the print bed prior to printing
- ✓ The electronics should be protected from dust down to  $10\ \mu\text{m}$  (IP5)
- ✓ The electronics should be properly cooled to prevent overheating issues (max  $70^\circ\text{C}$ )
- ✓ The printer should run on 12V
- ✓ The printer should be able to operate on a grid fluctuating between 180 and 380 Volts
- ✓ The printer should be able to run off-the-grid for at least 5 minutes during an outage
- ✓ The printer should be able to resume printing after a longer outage has been resolved
- ❖ The printer should be compactly transportable, without risk of damaging components
- ✓ The printer should be delivered partly assembled
- ✗ The printer should be easily transportable when it is fully assembled
- ✓ The printer should be carryable by an average person (max weight  $10\text{kg}$ )

## Chapter 7.2

# Conclusion

*In addition to an evaluation based on the list of requirements, a group of experts have shared their opinions on the final design of this project. Important conclusions can be drawn based on these evaluations.*

### Expert evaluation

The core of the design phase was aimed at finding solutions for the challenges of (1) frequent power outages, (2) excessive dust and high temperatures and (3) maintaining a maximum printing uptime. The experts all regarded the found solutions to adequately tackle these challenges. Naturally, more work can be done, but these proposals form a solid base.

The last two challenges concerning (4) connectivity and use and (5) transportability, were addressed only on a conceptual level in this project. Unsurprisingly, the experts regarded the solutions to these challenges uncomplete. A considerable amount of extra work needs to be done in these areas to create adequate solutions.

Looking at the broader picture, it seems that the final design forms a well fitting match to the context of a Sub-Saharan country like Kenya. Unlike any other 3D printer currently on the market, this design is able to deal with context specific challenges.

However, the general consensus is that the final solution has not been tailored enough to the intended usage of producing medical equipment. More time could be invested to find specific needs and requirements for the production of medical equipment, as well as looking into fields like quality control and assurance.

### Evaluation of requirements

The evaluation of requirements clearly shows what areas have not been addressed during this project. Most of these areas were outside the scope of this project, such as developing a dehumidifying solution to keep the filament dry.

Other areas that were addressed did not reach the required level to satisfy the requirements. For example, a requirement was that the printer should be easily transportable once it was fully assembled. Although printer transportability was addressed, this specific requirement was not.

Another example is the requirement that the printer should be easy to use by anyone with minimal instructions. Although a conceptual solution for this area was developed, no attention was given to the details of such a system. Plenty of work is left to be done in this field.

The next chapter, Recommendations, will dive further into how requirements like this could be addressed.

### Business model

What has previously not been mentioned in this thesis, is that apart from the final design proposal, also a business model was developed. This business model addresses the question of how a 3D printing system can be setup in Sub-Saharan Africa. It envisions that entrepreneurs should be educated to start their own 3D printing business, in which they can start to produce parts for hospitals and their local communities. The complete business model can be found in Appendix U.

### Final thoughts

Although initially not predicted, a significant amount of effort and time has gone into the analysis phase. During this phase a wide range of challenges and opportunities were discovered for 3D printing in Kenya, as well as many valuable insights that have direct implications for the design of a 3D printer in this setting. This can primarily be used for the development of a 3D printer for low resource settings, but might also be valuable for initiatives working on closely related products in a similar setting.

The solutions that were developed for the final design proposal are primarily aimed at 3D printing in a context like Kenya. However, several of these solutions are also much more widely applicable. For instance, the part ejection system could have far reaching benefits when installed on 3D printers used by companies and institutions. E.g. the faculty of industrial design could double the productivity of their printers if they were able to automatically eject parts, as this would allow the printers to be producing continuously, even during the night and weekends. It would also allow for a print queue to be setup, that students could access from online. This would end the annoying problem of students claiming 3D printers for days, and remove the hassle with SD cards.

## Chapter 7.3

# Recommendations

*In this chapter several recommendations are provided for further research and development of a 3D printer for healthcare in Sub-Saharan Africa.*

### Power supply

The designed flexible power supply with backup battery is considered an effective and adequate solution to deal with frequent power outages and surges. However, preliminary tests performed during this project indicated that it might be challenging to get such a power supply fully functional. For instance, battery lifetime might drop fast due to heavy demands of the printer. Another concern with the current setup is that during heavy 24/7 operation, the battery might get slowly depleted if the charger cannot keep up. As shown in Appendix N, the printer will draw a considerable amount of current, which might require a custom designed charger.

Therefore, the suggested approach is to design and develop a smart charger/power supply that can power the printer independently of the battery, and will switch to battery power only when the power is cut. In this case the charger will need to be strong enough to both recharge the battery, and power the printer, once the power is back on. The next step in this approach is to perform long term testing to see whether the system is able to maintain operation.

### Electronics enclosure

The designed electronics enclosure is an affordable solution to keep the controller board cool and free of dust. Preliminary tests have indicated that this enclosure will stop most dust from entering. However, it also exposed a flaw in the current design. One of the corners of the lid was designed to slide in a notch of the enclosure, to make it easier to remove. This corner was found to pose as a weakness in terms of dust sealing.

Apart from dust, dripping or splashing water can also have disastrous effects on the electronics. This was not addressed during this project, although especially in a country like Kenya, heavy rains can lead to leaks, which can pose a very real and potential threat for the electronics.

Therefore, a new iteration of the enclosure should be made with the goal of (1) fixing the described design flaw of the lid and (2) making the enclosure drip water tight.

This is in line with an Ingress Protection rating of IP51. It is also recommended to perform professional IP tests to confirm this rating is satisfied by the new design.

### Automatic part ejection system

This system provides 3D printer users with a new way to increase the uptime of their printer. Since it is envisioned that 3D printing medical equipment for healthcare can best be executed by local entrepreneurs, maximizing printer uptime is of vital importance.

The current solution is considered effective in most cases, but it also has its flaws. During the final test, a problem occurred where the 3D printed part would roll off the part catching system, ending up getting stuck between the bed and the frame. Problems like this can have disastrous effects if someone is relying on a printer that will autonomously produce parts throughout the night. Luckily this particular problem is easily solvable by extending the size of the part catching system to the full width of the printer.

However, it does illustrate a major concern with this system: Reliability. When problems occur and there is no one around to stop the printer, things can go badly wrong. There are two approaches to tackle this concern. First, one could improve the part removal system up to a level where it will remove every type of part 100% of the time. The second approach involves including a safety monitoring system that will stop operation as soon as a problem is detected.

This last option is considered the best and most feasible approach, and can easily be implemented by utilizing the stepdetection algorithms already included in the processor.

Improvements can also be made concerning the active cooling system. This is currently comprised of two blower fans. Other fans have not been tested, so this should be done first. Another interesting idea to investigate, is to use Peltier elements to build a heated bed that can instantly be turned into a cooled bed, by switching current flow. This could drastically decrease cooling time, and thereby increase ease of part ejection.

Lastly, a simple but useful improvement is to add a thin piece of rubber underneath the part removal arm, that can act as a cleaning sweeper, much like a windshield wiper, to clean the bed after every print.

### Connectivity and use

As was accurately pointed out by Ben and Tobias, chapter 7.1, there is still a lot of work to be done concerning the useability of the 3D printer. Currently a conceptual solution has been hypothesized that allows users to operate the printer with their smartphone. However, the exact details and functioning of such an app can still be considered a black box.

There is currently no data available on using a 3D printer with an app, and there are even more uncertainties when it comes to using such a system in a country like Kenya. Therefore, the first thing that needs to be done is to perform an extensive user research in a Sub-Saharan country, like Kenya. This research should be aimed at (1) finding and mapping users that are able and willing to operate a 3D printer, and (2) assess their technical capabilities in terms of using such an app, and performing simple repairs. This data can then (3) be used to come up with criteria for the design of the envisioned smartphone app, which is the last step (4) of this approach.

When tackling this challenge, one should also consider 3D print order requests, sending files to the printer and lastly printer monitoring and maintenance.

### Transportability

The solution that was developed in this area can be seen as the starting point for further development. Arranging the printer in the partly assembled state as shown in chapter 5.6, page 92, will allow for more compact shipping, but whether the fragile parts of the printer will remain undamaged during a bumpy ride, is still questionable. This also very much depends on the type of packaging used. Ideally one would ship the printer in a sturdy case, such as an aluminum toolcase. Unfortunately these are often quite expensive.

As already mentioned in the previous chapter, another aspect that was not fully addressed was portability: Making sure the printer can be easily moved or carried once it is fully assembled. The flexible power supply aids in this, but it is not enough. There is currently no easy way to carry the printer.

A simple approach to tackle this problem would be to design a 3D printable hand hold that can be easily attached to the top of the frame.

### Other areas

Besides the areas that were fully or partly addressed during this project, there are also areas that were not addressed at all. This includes quality control, repairability, scheduled maintenance and local manufacture.

### Quality control

When using 3D printing for production of medical equipment, it may be important to ensure a certain quality standard is met every time. Although this has not been mentioned in this thesis, quality control has been a point of interest during a bigger part of the project. Unfortunately time did not allow for going in-depth, and therefore this was not included in the thesis.

Envisioned solutions to tackle the challenge of quality control involve using image processing with low cost camera modules, or using a weight measurement system. This last idea is particularly interesting, as it combines perfectly with the automatic part ejection system; the part can be ejected onto a weighing platform, which assesses its quality. More on this can be found in Appendix J.

### Repairability

From the context analysis it was found that it is very important that the printer is easily repairable with mostly locally sourced components. During the final phase of the thesis, this area was briefly touched upon, and a quick repairability assessment of the printer was performed, see Appendix I. The conclusion was that the printer is already relatively easy to repair, and that efforts should be focused on other areas first, such as useability of the printer.

### Scheduled maintenance

According to Ben and Tobias, Kenyan maintenance mindset usually goes along the lines of “if it aint broke, don’t fix it”. In other words, they will only start to address a problem once it stops the machine from functioning. To address this behaviour, solutions should be considered that schedule maintenance, and somehow incentivize users to do this maintenance at the time when it is needed

### Local manufacturing

It is hypothesized and envisioned that the proposed 3D printer can be built locally in a city like Nairobi. However, there is currently not enough data available to prove this hypothesis, and therefore this should be tested on a trial and error basis.

## Chapter 7.4

## Reflection

*In this final chapter of my thesis, I will take the opportunity to look back at the project and reflect on my process and experience.*

It is strange to realize that I am already at the end of my thesis, and thus, the end of my studies at the TU Delft. The final thesis was something that I both looked forward to, as well as dreaded. I am quite perfectionistic in nature, and therefore envisioned that my thesis had to be the final showpiece, the ultimate crown jewel, the Crème the la Crème - of my studies.

In hindsight, I think such high expectations and ambitions are not a good start for a thesis, or for any project in that sense. In my case this resulted in high levels of unnecessary stress. Many times during the course of my thesis I would wonder what exactly I was doing, whether all this work would actually be useful, and ultimately, I was afraid to fail horribly. I had never before experienced such doubts and levels of stress as I did during my thesis.

I think this can mostly be attributed to the fact that until now I have usually worked in teams of at least two people. In that case the collective nature of the team removes a big part of the individual burden and stress. Although working on my thesis was not always pleasant or relaxing, it did teach me a valuable lessons:

*When I am walking an unknown path, with an unknown destination, I can worry myself sick all the way about what I will find at the end. But what does this worrying really amount to? Nothing. Therefore, it is best to just trust myself, have faith, and instead of worrying about some uncertain future, rather focus on taking steps here and now.*

But apart from the stress and worrying, I also had many very good experiences during this thesis. First and foremost on that list, is the field trip to Kenya. I had never been to any country in Africa before, and so I fell with my nose in the butter, as we say in Dutch. This two week trip brought me an abundance of new experiences that I will never forget. The fact that I was on my own, having to plan and arrange everything myself, made it all the more fun, and turned the trip into one big adventure.

Apart from opening my eyes on a personal level, the field trip also enlightened me on a more academic level, in relation to this project. Many of the assumptions I had

made during the preliminary analysis, turned out to be completely different, and I had to change my focus several times. Moreover, I made several strong connections that might come in very handy if I choose to pursue what I have started to unravel with this project.

During the design process of most of my projects, I tend to follow my own methods rather than following those found in books like the Delft Design Guide [13]. This often results in a slightly chaotic and unsystematic approach, as was also the case during a better part of the design phase of this project. In part, this method can be quite useful, as it allows me to try many different ideas very quickly, but on the other hand, I end up with a mess that I need to clean up and process before it can be presented as something useful.

Along the course of my thesis, especially towards the end, I developed a more systematic approach. I start by defining what I need, e.g. a graph showing power consumption of the 3D printer running on a battery. Then I figure out how I can gather this data, e.g. by doing a simple test. I gather the required items, such as batteries and multimeters, and write down a method for what I want to do. Besides taking notes, before, during and after the process, I also take many pictures. Finally I end up with a bunch of data and pictures that can easily be processed into something useful.

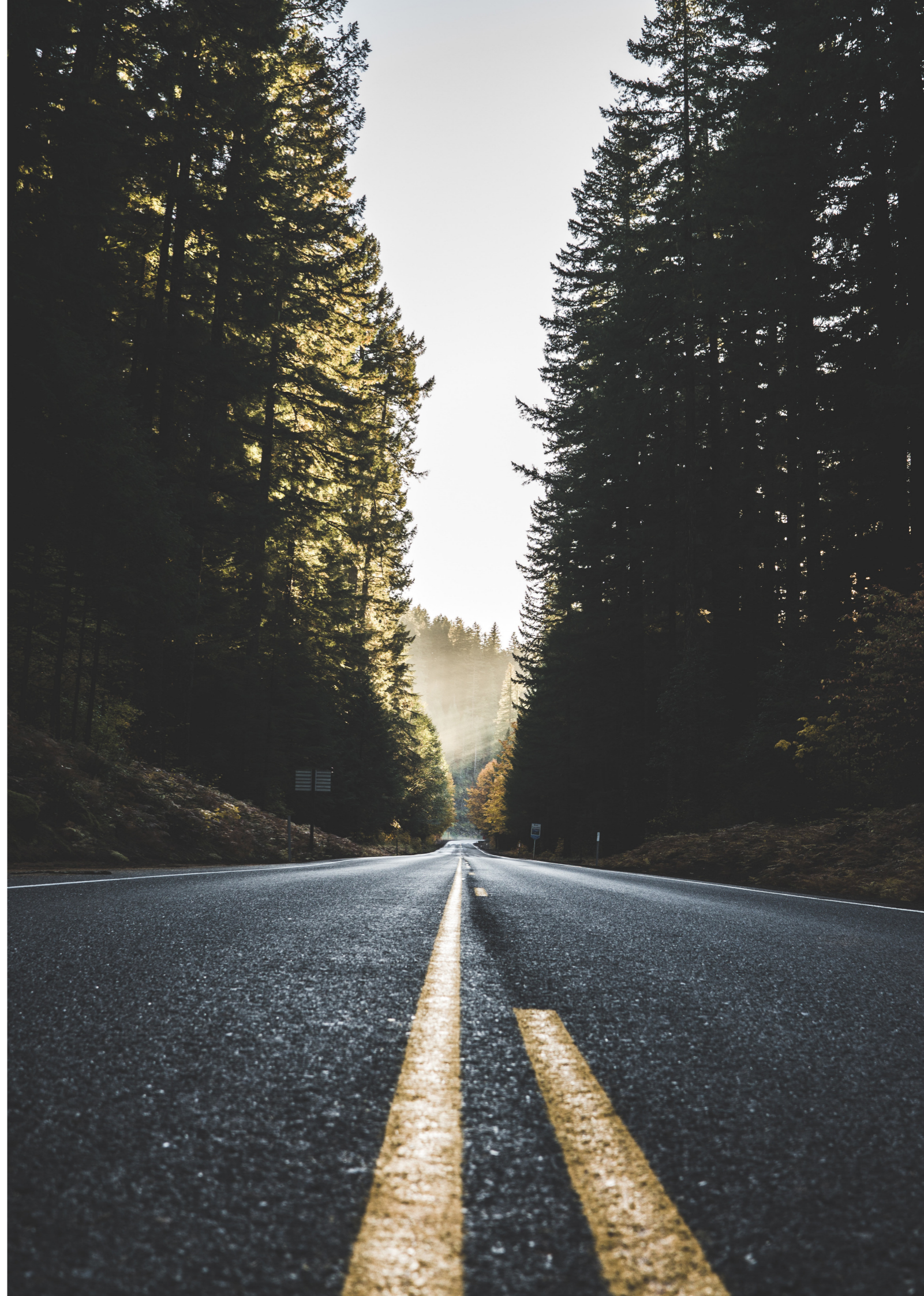
At the start of the project I setup four personal learning ambitions:

1. Getting in-depth knowledge in the field of 3D printing, and more specifically FDM printing
2. Getting familiar with conditions in African countries, and more specifically Kenya
3. Getting familiar with designing for emerging economies
4. Strengthening my competences in the field of project management and planning

I can happily conclude that each and every one of these ambitions have been fulfilled, probably even more than I had hoped for at the start.

Looking at the final result of my thesis, what you have in front of you now, I think that there was never a need to worry.

In the end, the final result might actually have become the ultimate crown jewel, the Crème the la Crème - of my studies, and to be honest, I am quite proud of it.





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