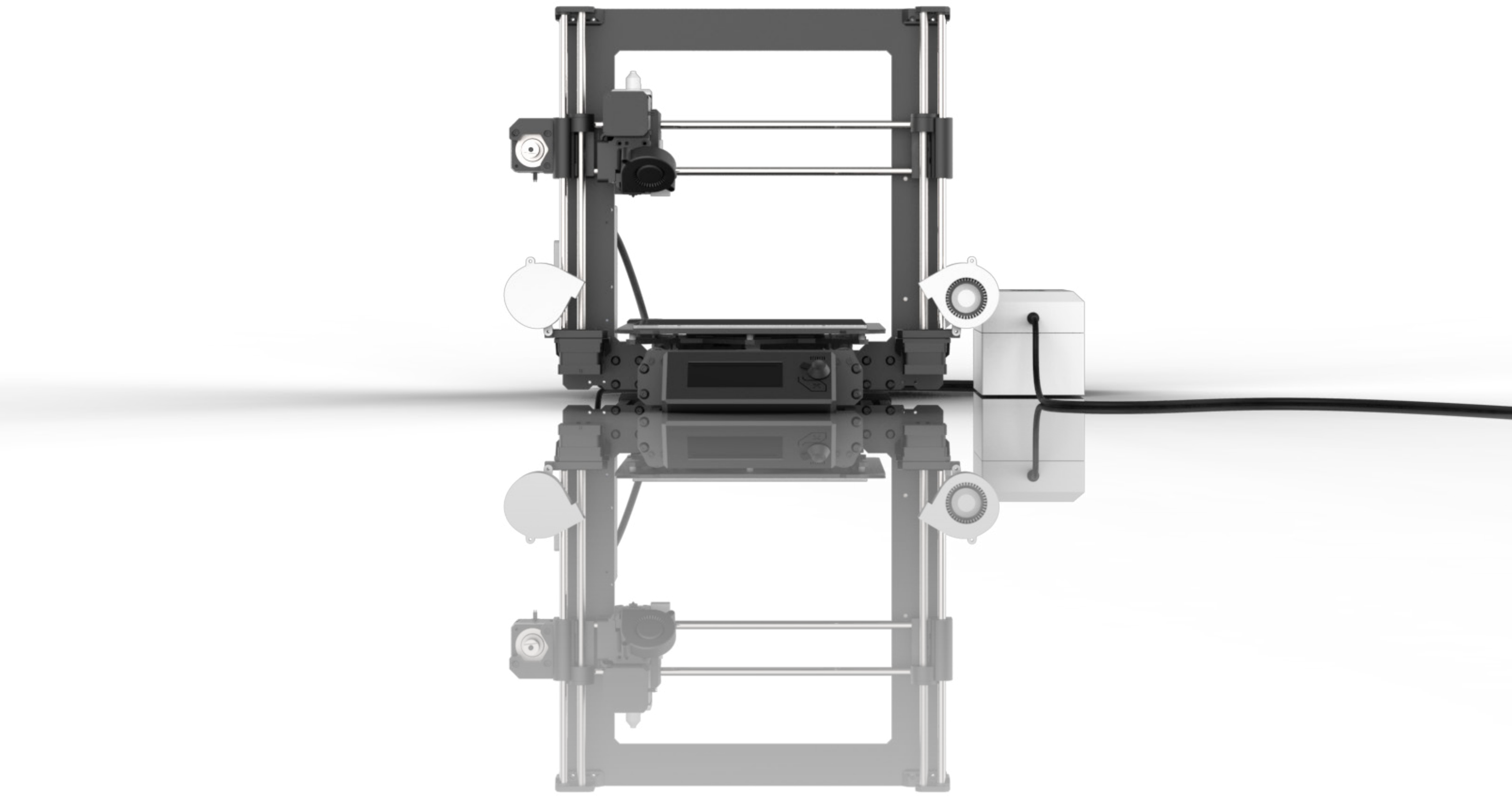
Design of a 3D printer
for healthcare
in Sub-Saharan Africa

APPENDICES



Ludo Hille Ris Lambers

MASTER THESIS
Integrated Product Design

Delft, July 2019

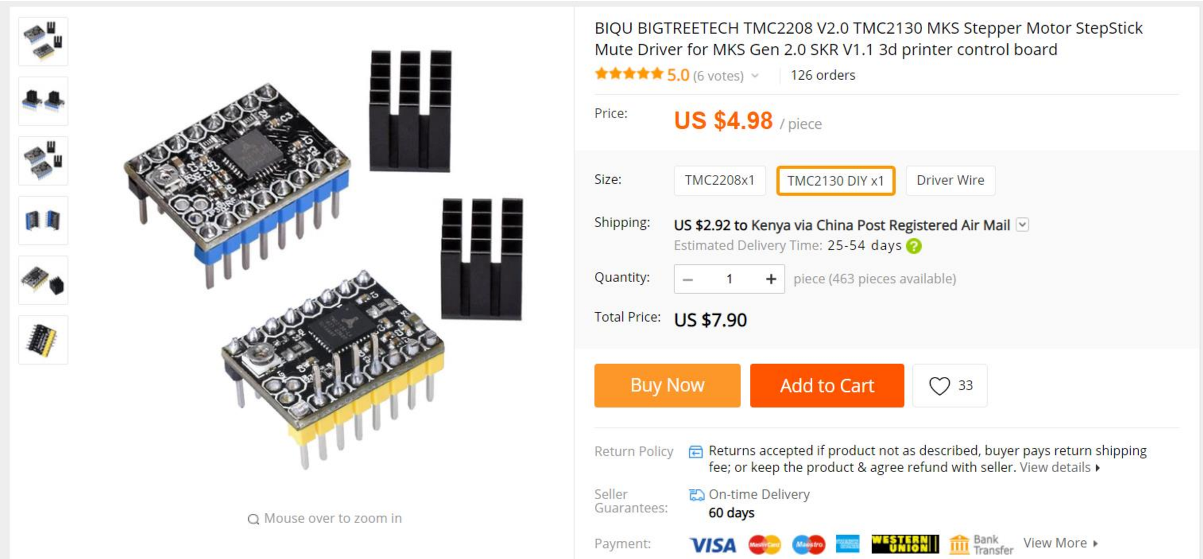
Table of contents

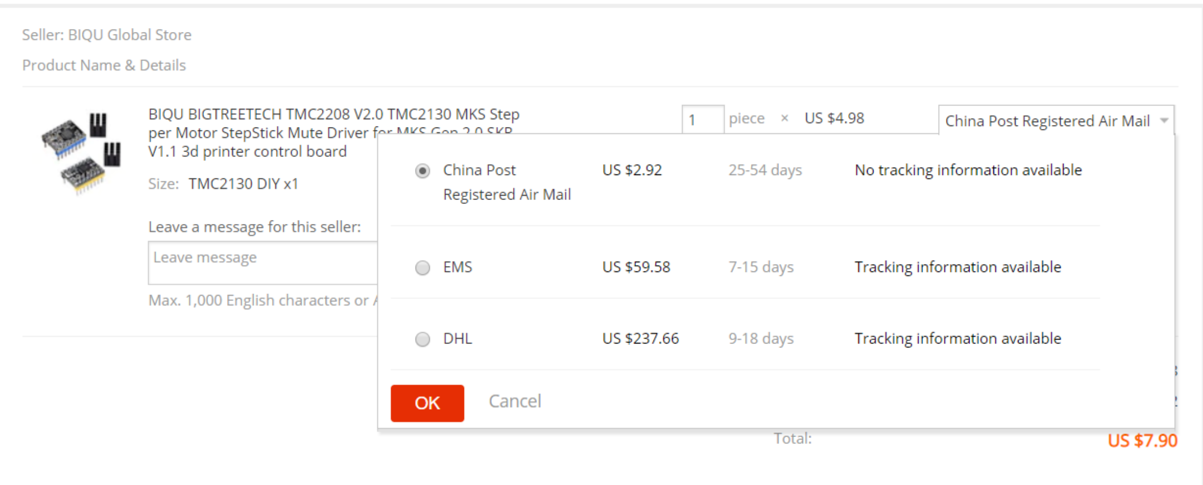
Appendix A

Shipping goods to and in Kenya

AliExpress

Data retrieved from AliExpress [1].



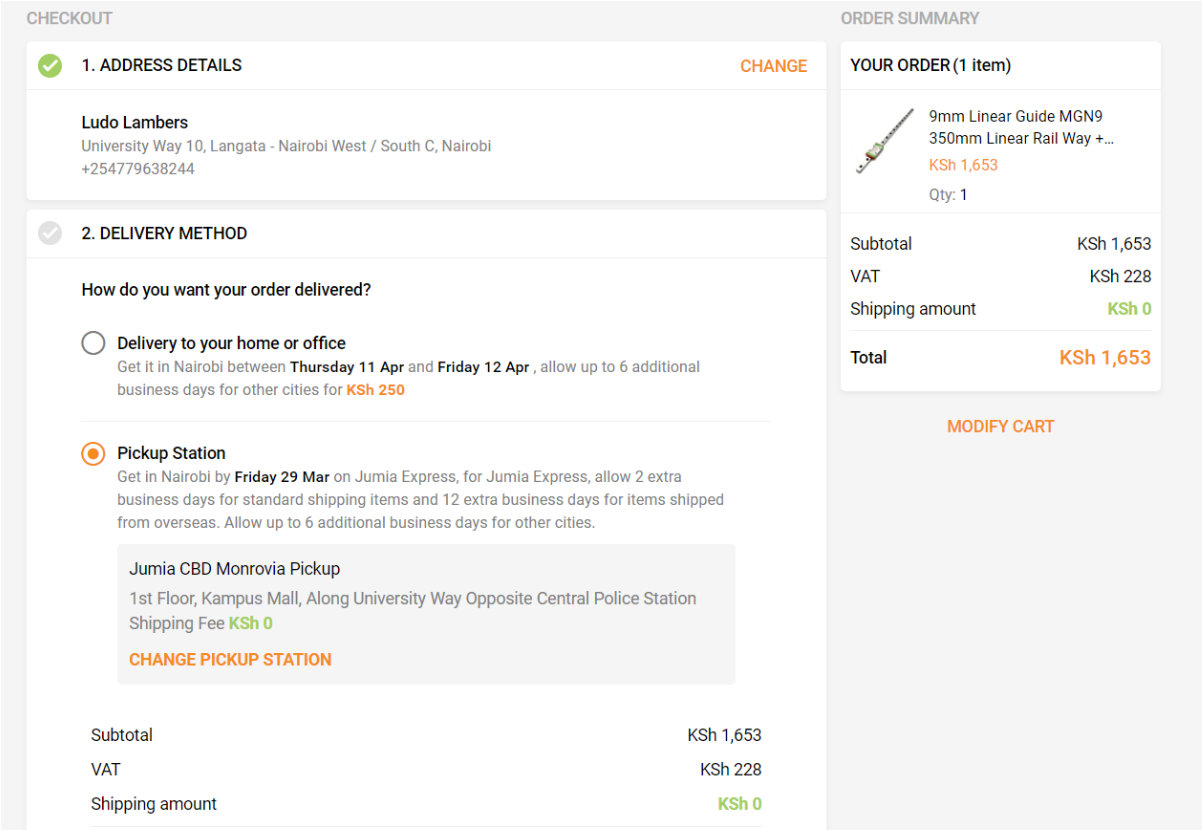


Conclusion

Shipping a singe small part will cost $2.92 through China Post Registered Air Mail, however, this can take 25 to 54 days. The next option is shipping through EMS, which can ship items in 1 or 2 weeks, but this will cost $ 58.98.

Jumia

Jumia is Kenya's leading electronics webshop [2].



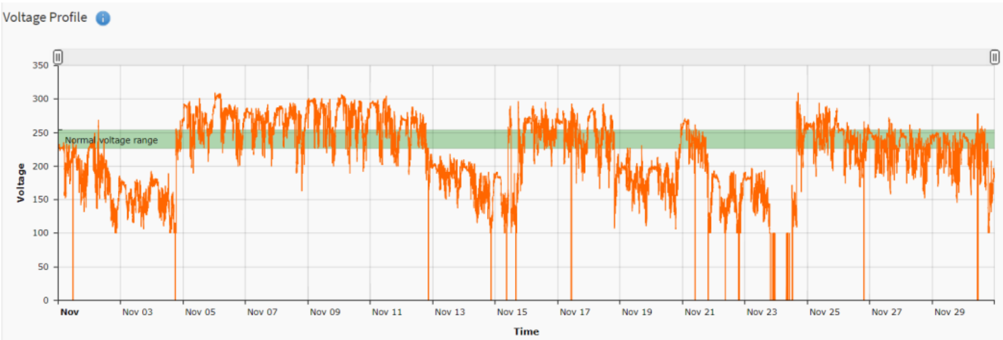
Conclusion

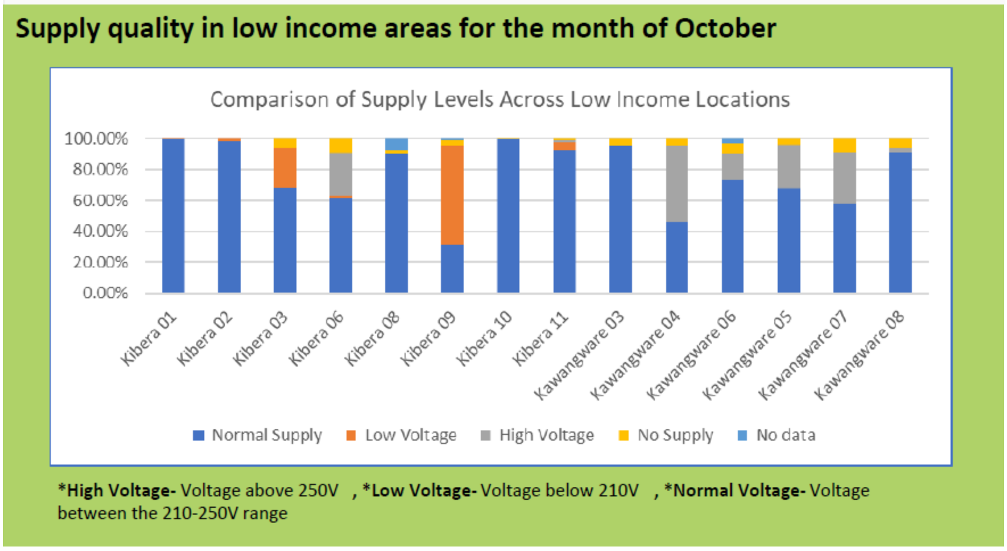
Shipping items from Jumia only costs around 250 KSh, which converts to roughly $ 2.50. Shipping can take between 1 and 2 weeks. Note: The item shown above has to be shipped from overseas, just like with AliExpress, and shipping here takes approximately the same time, but the cost is only a fraction of AliExpress shipping costs.

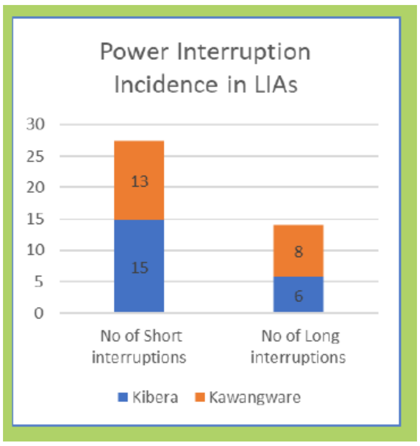
Appendix B

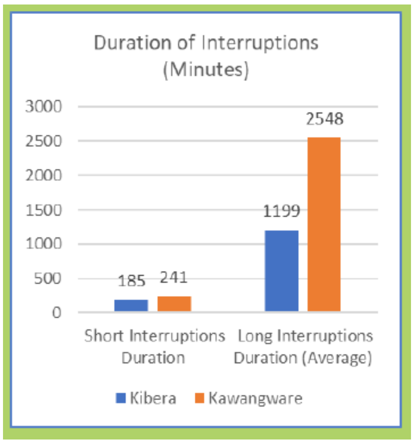
A short analysis of Kenya's power grid

According to a survey ESMI Kenya [3], in Kibera District, Nairobi, voltage can fluctuate between 100 and 300 Volts, with an average of around 250 Volts. In a single month, as many as 15 short power interruptions can occur, as well as 8 long interruptions. These can last around 30 minutes for short interruptions, and 3 hours for longer interruptions.









Appendix C

General FDM Desktop 3D printers

According to 3DHubs, the most used FDM Desktop 3D printers are [4]:

#	Printer Model	Manufacturer	Price	3D Hubs Rating
1	Original Prusa i3 MK3	Prusa Research	$ 881.00	8.8
2	Original Prusa i3 MK2	Prusa Research	$ 726.00	9.1
3	Creator Pro	FlashForge	$ 1,199.00	8.1
4	Ultimaker 3 Extended	Ultimaker	$ 4,295.00	8.9

For the most interesting comparison, the Prusa i3 MK2 is left out, and the DeltaWASP 2040 Turbo2 is added, as this is a delta printer that can achieve great speed results.

Comparison table of the four printers:

	Original Prusa i3 MK3	Creator Pro	Ultimaker 3 Extended	DeltaWASP 2040 Turbo2
Price	$ 880.00	$ 1,199.00	$ 4,295.00	$ 3,500.00
Build volume	25 x 21 x 21 cm	22.5 x 14.5 x 15 cm	21.5 x 21.5 x 30 cm	20 x 20 x 40 cm
Minimum layer height	50 micron	100 micron	50 micron	50 micron
Extruder head	1	2	2	1
Open source	Yes	Yes	Yes	Yes
Heated bed	Yes	Yes	Yes	Yes
Filament diameter	1.75 mm	1.75 mm	2.85 mm	1.75 mm
Connectivity	SD	USB, SD card	SD, USB, WiFi, Ethernet	SD
Max printing speed*	200 mm/s	200 mm/s	150 mm/s	600 mm/s [5]
Power panic function	Yes	No	No	Yes

* Maximum printing speed is a very unclear parameter, and is actually dependent on a number of other parameters. Most printers theoretically can reach travel speeds of 300 mm/s, but this does not mean that they can print at this speed. This data is also not available for most printers, except for the DeltaWASP printer. The printing speeds for the other printers were estimated, based on YouTube video's from users.

Appendix D

Dimensions of medical equipment

Kats *et al.* [6] composed a list of hospital supplies well suited for 3D printing. The most interesting of these parts are single use, low volume parts. In this short study the dimensions of these items will be estimated.

Method

The most suitable parts for 3D printing were extracted for the list from Kats, and for each of these parts, dimensions are estimated through a quick google search, based on images and information.

Item	Estimated dimensions (X Y Z) [mm]
Cause Bracelets	80 x 80 x 10
Tongue Depressor	100 x 10 x 2
Tweezer	100 x 10 x 10
Surgical Retractor	120 x 10 x 40
Hemostat	150 x 60 x 5
Kidney Dish	250 x 130 x 80
Forceps Cheatle	300 x 80 x 10
Forceps Pliers	200 x 60 x 5
Glove Hook	60 x 40 x 10
Scalpel	150 x 10 x 4
Forceps Compound	120 x 75 x 5

Forceps Cheatle, adopted from AMDNext.com

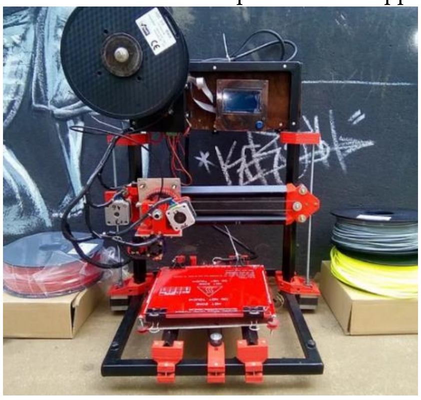
Conclusion

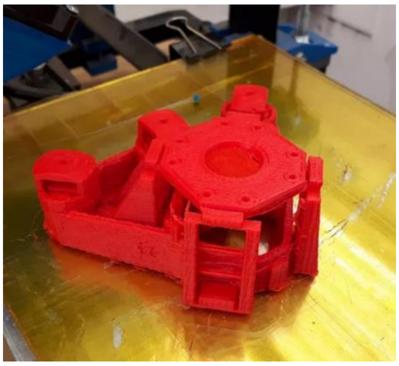
None of these items required support or multi material, and they are all very well suited for 3D printing. The largest dimension was found to be 300 mm in X or Y direction, and the largest Z dimension was found to be 80 mm.

Appendix E

AB3D printer analysis

African Born 3D printing, or AB3D, is a Nairobi based startup that produces 3D printers from locally sourced material like metal tubing. The printer is created RepRap style, meaning it is composed of many 3D printed parts. A bill of materials of the printer was supplied by Karl Heinz, CTO of the startup.

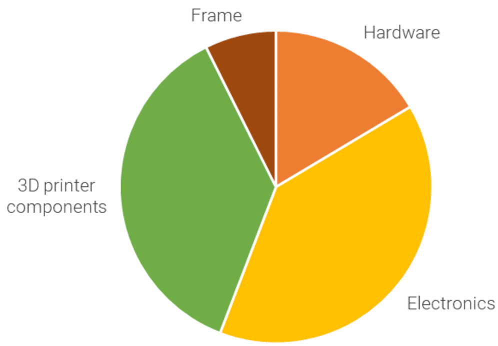




Cost breakdown

The total production price of the printer is $ 215.

Hardware	**$ 35.27**
Screws, nuts, washers	$ 10.19
Bearings	$ 8.91
GT2 Timing belt	$ 4.00
GT2 Pulleys	$ 6.00
Other hardware	$ 6.16
Electronics	**$ 84.47**
Arduino Mega	$ 8.00
RAMPS 1.4	$ 20.00
12864 LCD Screen	$ 7.00
Power supply	$ 32.00
Switches, cables and crimps	$ 17.47
3D printer components	**$ 78.90**
Heated bed	$ 12.00
Motors	$ 39.20
Hot end assembly	$ 27.70
Frame	**$ 15.85**
Metal square tubing	$ 2.72
Aluminium plate	$ 1.82
Painting	$ 2.48
Welding	$ 7.97
Cutting	$ 0.86
Total	**$ 214.48**



Karl also shared the following list containing estimated prices locally purchased recycled electronics, other materials and prices for plasma and laser cutting:

Item	Cost
Stepper motors (1kg)	$ 1.00
Fans (1kg)	$ 1.50
PSU	$ 5.00
12V Lead acid battery	$ 5.00
Steel sheet	$ 15.00
Wood sheet (4x8 foot)	$ 20.00
Plasma cutting steel sheet	$ 15.00
Laser cutting wood sheet	$ 10.00

Appendix F

Kenyatta National Hospital visit

Day 1

Date: 28/05/2019

Location: Kenyatta National Hospital, Nairobi

Department: Labor ward

Main respondent:

Grace Wan'gombe
Nurse officer / manager of the labor ward
+254722622931
Gwangechi62@gmail.com
Has worked for 34 years at KNH
Studied nursing at Kenya Medical Training Center (KMTC)

Attendees:

Those present were:

- Grace: The main respondent and nurse officer of the labor ward
- Edwins: Contact person that got us in, works in administration
- Ishmael: My local friend and assistant from the MakerSpace
- Myself: I conducted the interviews and lead the conversations

Introduction and tour of the labor ward

We started in Grace's office. One of the first things I did was to ask Grace what she thought the machine (the 3D printer) was for. She thought it was some kind of medical suction device. After I explained what it really was, she indicated she had never heard of a 3D printer before. I had to show some examples of 3D printed parts for her to get a feel and understanding of what the machine could do. Shortly after showing this, she understood the concept, and became very excited and enthusiastic.

Before getting to business and starting with the interview, I asked Grace if she could show us around the ward. She was happy to do so, and while showing us around she quickly started showing devices she (correctly) thought could be 3D printed. She and other nurses around her were very interested in the 3D printed sample laryngoscope that I had brought along. They especially saw a great potential in disposable 3D printed equipment. **Insight: The nurses and midwifes are not always certain that the equipment they are using has been properly sterilized, and are often afraid that bacteria or spores are still present on the devices.** Therefore, the idea of sterile disposable 3D printed equipment (like a laryngoscope) greatly appealed to them. Grace also shared some facts about the labor ward: They do around 60 deliveries every 24 hours. The ward owns around 30 beds. This means that often two women will have to share a bed prior to, during, or after delivery**. Insight: When using 3D printed disposable items in this ward, they would require at least 60 sets of items every 24 hours.**

Grace explained exactly what steps are taken to sterilize their equipment directly after use:

1. Decontamination: The equipment is put in a decontamination bath (usually JIK)

2. Washing: The equipment is then washed with soap and water
3. Rinsing: The equipment is rinsed with still tap water
4. Drying: Equipment is left to dry
5. Autoclaving: The equipment is transported to a central sterilizing unit, where it will be put in an autoclave together with other equipment. Since they have no view or control over this process, they are not always certain that equipment is actually properly sterilized

Figure 1: Steps 3 and 4 of the sterilization process happen here.

Figure 2: A broken suction machine

Figure 3: Fetal scope, a device every midwife must carry at all times (cost price ~ $2)

Figure 4: Two types of Laryngoscopes (with integrated LED)

Figure 5: Speculum in kidney dish

Figure 6: Umbilical cord clamp

Interview

Next I conducted an interview at Grace's office. The interview started off with prepared questions, but quickly flowed naturally through several important topics that were discussed thoroughly. General results and findings are summed up as follows:

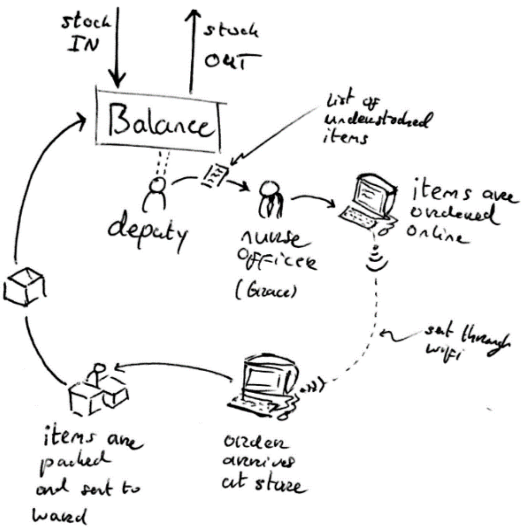
- The hospital is equipped with wifi, coverage throughout the entire hospital
- There is no scarcity of computers. The labor ward alone already has 4 computers.
- In case of a power outage the backup generator always kicks in. This takes a few seconds and can take over power production until grid is functioning again.
- The best place to station the 3D printer would be the biomedical engineering department
- The labor ward works hand in hand with the biomedical engineering department
- Best people to maintain and operate the printer would be biomedical engineers
- When nurses see and feel that the equipment they use is plastic, they will assume it is disposable, and probably dispose it after use
- Autoclave is preferred method of sterilization as it can even kill bacteria spores
- Chemical decontamination is usually done with JIK
- Other decontaminates include: Endozyne and precept
- Both Grace and Edwins estimated the cost of the printer at 200.000 KSh ($2000)
- They think this is also the maximum amount the hospital would pay for such a machine
- If the 3D printing environment is not enclosed, dust can cause parts to be contaminated, and thus sterilization cannot be guaranteed.
- The machine needs to be portable because biomedical engineers will want to be able to move it around easily

Getting to the heart of the problem

At some point the discussion moved towards the problem of equipment shortages. Grace had already briefly touched on the subject by indicating they have 30 beds, while every day 60 mothers come in to deliver their babies. I asked her if they ever have a shortage of equipment, such as fetal scopes, speculums or umbilical cord clamps. She indicated this was often the case, and that the reason for this was "limited resources". She went on to explain that they also frequently suffer from delayed delivery, or understocking, e.g. they will place an order for 4000 rubber gloves, but receive only 2000 the next week. The heart of this problem lies in an inefficient procurement process, where a lot of bureaucracy is involved, leading to long lead times.

Understanding inventory management and stocking

Grace explained how inventory management and stocking of items works. The process is visualized with the sketch on the right.



Grace's deputy is in charge of inventory management. She keeps a balance of the stock going in and out, and daily provides Grace with a list of understocked items. Grace in turn uses this list to order items on her online system. This is sent to the hospital store, where store workers find and pack the items Grace ordered. These are then sent to the labor ward. This process can take hours, if, and only if, the store has the items stocked. Problems start to occur once this is not the case. Now the store needs to order new items. It can take weeks or months until the store will be restocked, and is finally able to fulfill Grace's order. In this case shortages are unavoidable.

What happens in case of a shortage

In this case the nurses and midwifes need to improvise. They will use substitutes for the items that are missing. E.g. when they run out of umbilical cord clamps, they will instead use a small string of rope to tie of the umbilical cord.

However, these substitutes cannot be found for all equipment, so in some cases patients will need to wait until the limited equipment that is being used becomes available again.

Day 2

Date: 29/05/2019

Location: Kenyatta National Hospital, Nairobi

Department: Biomedical engineering department

Main respondent:

Regina
Medical Engineering Technologist
Age: 47 y/old

Interview

The 3D printer was demonstrated for Regina. She could not guess what the machine was for. After I explained, she still did not really understand the purpose. I showed some examples of 3D printed medical tools (laryngoscope and pliers), and she immediately had many concerns. She was not very cooperative at first, and instead of answering questions, kept going on about the concerns she had about the machine. Her main concern was that people (and I suspect this includes her) don't like change, and therefore will not appreciate such a machine. Doctors will not want to switch to plastic equipment, when they are used to using e.g. a metal laryngoscope. **She also indicated she was really not interested in having "yet another machine".**

Operator user test

To assess the difficulty of two maintenance tasks, a simple user test was constructed, in which the participant (Regina) was asked to perform a set of two tasks:

1. Load filament
2. Calibrate Z height through first layer calibration

I asked her to perform the first task without any form of instruction. The second task was too complicated to ask her to perform without instruction, so I demonstrated it once to show her how to do it.

First test: Loading filament

After I asked her to perform the first task she was very hesitant at first. She did not want to try anything without consulting some kind of instruction manual. It felt very unnatural for her, but she proceeded anyway after some motivation from me. She immediately understood where to put the filament, and after inserting it in the extruder, the filament was automatically pulled in (due to the filament sensor). She kept her fingers on the filament just above the extruder, as she felt it being pulled in. After that the LCD prompted her if the filament was being extruded in the correct color, and she pressed the button to indicate this was true. All in all she did the task very well, especially seeing she did not get any instructions. Another interesting note is that she was quite insecure whether she performed the task correctly, until I told her she did.

Second test: Calibrating Z height

I started the first layer calibration routine for her on the LCD screen, and then asked her to perform the calibration. She was very hesitant at first, but after a while gave it a go anyway. It was obvious that she has no idea what she was doing, and was just fiddling with the knob a little bit. The result in the end was quite good, but that had nothing to do with her performance, as she actually did not change the Z height enough for any difference to occur.

Insights

- Loading the filament was very easy and intuitive. The filament sensor seems to be a great asset, as it is the cause of this task being so easy.
- Calibrating the bed is a very difficult task, that requires knowledge, experience, and a good eye.
- A step-by-step instruction manual is something the biomedical engineers are very accustomed to, and heavily rely on.

User test: Design a 3D printer

Method

A user test was performed in which the participants were asked to "design" a 3D printer for production of medical equipment in a hospital like KNH. They were given a set of cards from which they could choose a starting point, and several add-ons to come up with a final design. One of the participants was given cards without cost price of add-ons, the other participant was given cards where the cost price of each add-on was noted.

Results

1. **Grace**

She was given the cards without prices.

- Fully assembled printer
    - She did not give a clear reason why she chose this
- Quality control system
    - Because it is important that the produced parts are of an acceptable quality
- Battery backup system
    - In case the backup generator fails
    - This has never happened (in 34 years), but she likes being overly cautious
- Touchscreen
    - Because a log-in system is essential
- Continuous printing system
    - She thinks high productivity is very important
    - Consistent part quality is also very important

She did not choose wifi add-on because wifi is known to fail at times, and when this occurs, the entire hospital comes to a standstill. To avoid this, she thinks the machine should not be equipped with wifi. This is a typical strategy of choosing lower tech to reduce down time due to technical failures.

When I explained her that wifi could be used to connect the printer to her online ordering system, she responded very positive and actually changed her choice by including the wifi module in her design.

2. **Edwins**

Edwins was given the cards with cost prices.

- Partly assembled printer
    - To enhance capacity
    - This way biomedical engineers can train and learn while they assemble the printer

- Quality control system
  - It is vital to avoid bad prints
- Battery backup system
  - In case some 3D printers will be stationed at rural hospitals, this system will come in very handy
- Touchscreen
  - We need a log-in system to avoid mis-use
- Continuous printing
  - Same reasons as Grace
- WiFi
  - So that parts can be ordered to the printer online

The total costprice would come down to 54.000 KSh ($540), both Edwins and Grace thought this was a very good price.

3. Regina

She was given the cards with prices

- Partly assembled printer
  - "So we know how it works and understand it"
- Quality control system
  - She thinks quality is very important
- Battery backup system
  - Because the biomedical engineering department does not have a backup generator
- Touchscreen
  - She wants it, but is hesitant because it is so expensive
  - She was convinced when she learned about the log-in system it enables
- Continuous printing system
  - She was convinced that high productivity would be very important

Insights user test:

- Most respondents would rather receive a partly assembled 3D printer, so that they can understand how the printer works through the assembly process
- A battery backup system is wanted because not all areas have access to backup generator
- All respondents think that a continuous printing system is very important
- All respondents think that quality is important, as well as having a certain quality control
- All respondents are convinced that a log-in system is very important in the device

Appendix G

Cocreation session with Karl

Most common 3D printer problems in Nairobi, from personal experience with AB3D:

- Filament jam
  - This is either due to clogging from dust entering the nozzle, or filament drag.
  - Last issue was fixed by mounting filament spool on bearings
- Electronics failures
  - Clients either push the wrong button, or a connection on the board has shorted
  - Last issue can be solved by using higher quality boards and cooling them
- Basic maintenance laziness
  - Levelling the bed is sometimes too much to ask
- If many cables are visible on the outside, people will think it is not a finished product

Feedback on current design:

- Design the printer to guarantee 6 months of maintenance free printing
- Dust is honestly not such a big problem. Currently designed dust enclosure is more than adequate for the job. Current filament dust filter is equally adequate.
- Batteries should be secured, or people might steal them
- Cost price should not exceed $800
- Make sure cable management is done properly, this will evoke a feeling of a finished and high quality product
- Portability is important, it can open new opportunities, and will allow the printer to be handled and moved around: (verify this at hospital)
  - Make sure the whole printer can be picked up as a single package
  - Obvious use cue where to hold (and pick up) the printer
- Ease of use is very important, therefore:
  - Make sure the printer can be shipped fully assembled
- It is good to make the design modular
  - Part ejection system can be an interesting add-on
    - Not essential, as a full tray of parts can be printed in a single night, which equals, or even surpasses continuous printing with part ejection system
    - It generally takes longer to: print – cool bed – remove part – heat bed, instead of print – remove part – print
  - Battery pack can also be an add-on

Cost price:

- 1 kg stepper motors $1 (or $0.5 per motor)
- 1 kg fans for $1.5
- 1 PSU for $5 -> This can power the batteries
- 1 12V lead acid battery for $5
- Shipping goods from Aliexpress: $10 per kg, covers shipping + taxes
- Plasma cutting sheet material for frame: $15 cutting, $15 material
- Laser cutting wooden electronic enclosures: $5-10 cutting, $16-20 sheet (4x8 foot)

Connectivity and use:

- Use case 4 seems most interesting, since the system is centralized, seems most practicle, and can be enhanced with wifi
- Making users use internet is most probably not an issue (check with hospital)
- It should be so easy to use that doctors will know how to use it
- They need to log in somehow though

Main takeaways

- Printer should be designed to be transportable
- Printer should be designed to be rugged and repairable
- It is not realistic to station 3D printer at hospitals
- Better solution: Educate entrepreneurs to become 3D printer operators
- Humid and warm climate calls for filament dehumidifier
- Deliver the printer partly assembled: Kenyans want to understand the machine by building it
- To protect printer against dust, and ensure sterility: Full enclosure
- Kenyan solution solving is: Step-by-step, not out-of-the-box

Appendix H

Connectivity first ideas

Goal: The printer should have the ability to be operated without the need of a computer

Specific conditions

- There is a good cellular network coverage throughout Kenya
- Many people own smartphones
- Computers are a rarity in Kenyan hospitals
- WiFi is a rarity in Kenyan hospitals

Possible solutions:

- Jobs are sent to the printer via cellular network (3G/4G)
- Jobs are collected, and sent to the printer via Bluetooth
- Jobs are collected and stored on an SD card via smartphone
- The printer has an onboard control panel, from which it can be operated

Other solutions

It is also possible to connect the printer to the internet through cable (Ethernet), or WiFi. However, the context analysis showed that many hospitals do not have access to internet, neither cable nor WiFi.

Cellular network

By incorporating a SIM module into the 3D printer, it is possible to connect the printer to Kenya's cellular network. Since network coverage is good, this should be a viable option. In this case data can be sent and received through cellular network. Using this method it's possible to keep track of a *dynamic printing queue*, a list of print jobs that can be dynamically changed and updated. Another advantage is that the printer is able to communicate back. This could be used for e.g. notifying the printer operator that it requires new filament, or notifying staff that an order has finished printing.

Bluetooth

The printer can be operated with a smartphone via Bluetooth. This has been previously done in the Kijenzi printer, designed for Kenya [7]. Doing so will allow the printer to receive data via Bluetooth. In this case hospital staff, from for instance inventory management, will need to go around the hospital to list the items that are needed. This could be done on an app. When a queue has been made this way, it can be sent to the printer via Bluetooth.

SD card

The easiest solution (hardware wise) is to transport data to the printer by means of an SD card. This is currently also the widest used solution for moving files from computer to printer. However, since in this case files need to be transported from smartphone to computer, this solution brings some challenges. For instance, not all smartphones support an SD card. Also, these small chips are prone to be lost or stolen.

Onboard control panel

The last option does not require the personnel to use their smartphone, as an onboard control panel is used to prepare the printer for production. All print files will need to be stored on the devices internal storage. This way connection to the internet is not necessary.

Evaluation

Cellular data

Pros
- ✓ Best ease of use
- ✓ Allows for printer to communicate back
- ✓ Allows for remote maintenance
- ✓ Allows for remote updates
- ✓ Allows for a dynamic queue

Cons
- × Relatively expensive
- × Monthly sim costs
- × Higher risk due to network dependence
- × Only possible in areas with coverage
- × Forces employees to use a smartphone
- × Monthly costs can lead to organizational hassle

Bluetooth

Pros
- ✓ Relatively cheap
- ✓ Can be used anywhere
- ✓ Well established

Cons
- × Not easy to use
- × Printer cannot communicate back
- × Requires physical presence of smartphone
- × Forces employees to use a smartphone

SD card

Pros
- ✓ Cheapest solution
- ✓ Well established

Cons
- × Some smartphones are not able to store an SD card
- × Risk of losing the card
- × Worst ease of use
- × Forces employees to use a smartphone

Onboard control

Pros
- ✓ Does not force employees to use their smartphone
- ✓ Does not rely on internet

Cons
- × Expensive
- × Requires onboard computer like Raspberry pi

Conclusion

The SD card solution alone will never be a viable solution, as it requires quite a cumbersome way of working, and there is considerable risk of the card getting lost. Bluetooth has some advantages over cellular data, as it is more established in relation to 3D printing, and can also be used in areas without a cellular network. Using cellular data can open up a wide range of opportunities, like remote updating and maintenance, as well as a dynamic printing queue, and the ability to notify printer operators with the needs of the printer. The downside is cost, however these increases are relatively small. A sim module costs around $ 4 [8], and 2GB of data can be purchased for $ 5 per month from Safaricom [9]. Whether this is really the best solution is still questionable, as the monthly subscription cost could potentially be a deal breaker for hospital organizations. Moreover, this makes the printer inaccessible and unusable in areas without cell coverage. The last option, an onboard control panel, allows the printer to be used without the need of a smartphone, and independent of internet.

It is considered the best solution to combine cellular data with an onboard control panel. This way the wide range of possibilities that cellular data opens up, can still be harnessed, but the printer will also be usable without the need of a smartphone or internet.

Appendix I

Repairability

From the field research it became apparent that a very important feature of a printer for Africa should be repairability. Components will inherently fail over time, thus to maintain a high uptime, and make any business financially worthwhile, the printers should be easily repairable.

According to Guus van Bohemen, ex-IPD student who graduated with the design of a repairability assessment tool [10], the repairability of a product can be assessed with a set of 20 criteria.

1. Identification of the problem
2. Availability of a repair guide
3. Warranty issues
4. Technical knowledge
5. Availability of spare parts
6. Spare parts costs
7. Number of tools needed
8. Types of tools needed
9. Critical components are readily accessible
10. Repair actions needed
11. Number of screws
12. Removability of fasteners
13. Visibility of screws and other fasteners
14. Identification of the components/parts
15. Risk of injury
16. Environmental issues at end of life
17. Fragility or robustness of components
18. Internal organisation of components
19. Clarity of repairability
20. State after repair action

The full list can be found in appendix Fixme. The current Prusa printer was assessed with this tool, and this resulted in a score of: **Fixme**.

Most common issues that require maintenance

From the insights gathered during field research, and an article from Prusa [11], the following list of common issues that require maintenance was composed.

Issue	Required maintenance
Nozzle clogs	Unclog or replace nozzle
Thermistors break down	Replace thermistor
Dirty rods or bearings	Rods needs to be cleaned, bearings relubricated
Dirty extruder gears	Gears need to be cleaned and lubricated
Electronic connectors not properly connected	Connectors need to be reattached

For these maintenance jobs it is vital that one has easy access to the electronics, the linear rods and bearings and the inside of the extruder. It takes around one hour for an inexperienced user to take the entire extruder apart, and therefore this is quite acceptable.

Appendix J

Quality control

Goal: The produced parts should be quality checked to maintain a certain quality standard

Specific conditions

- It is envisioned that the printer will produce many parts per day (> 10)
- The printer will most probably be connected via cellular data

Possible solutions:

- Imaging
- Weight comparison
- Manual inspection

Imaging

By integrating one or multiple camera's into the printer, it is possible to perform a quality check, either automated by image comparison between a benchmark model and the produced print, or manually, e.g. from a remote location. This has been successfully done in the past [12].

Weight comparison

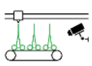
Another possibility is to include an automatic weighing station in the 3D printer, that can compare the weight of the printed object with a benchmark weight. It is assumed that this could work as a general quality check, but more research and testing needs to be done to verify this.

Manual inspection

The last, easiest and most affordable option is to have the quality of produced parts checked manually, for instance by the printer operator.

Evaluation

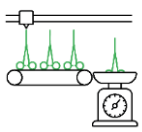
Imaging



Pros
- ✓ Can be automated
- ✓ Relatively well established

Cons
- × Expensive
- × Complicated

Weight comparison



Pros
- ✓ Novel technique
- ✓ Relatively cheap (low key hardware)
- ✓ Simple solution

Cons
- × Not well established

Manual inspection

Pros
- ✓ Easiest solution
- ✓ No implications for design

Cons
- × Requires training of personnel

Conclusion

Manual inspection will be a good starting point for this project. The other options are interesting for further development.

Appendix K

Morphological chart

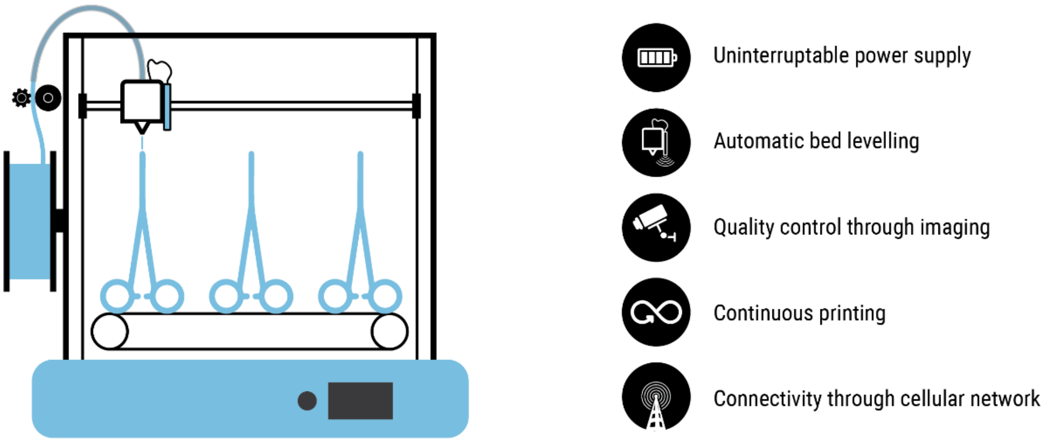
Frame type	Cartesian	Delta	Polar	SCARA
Feed system	Direct	Bowden		
Bed levelling	Manual levelling	Automatic levelling	Stiff frame	
Power supply	Surge protector	Uninterruptable	Power-loss recovery	
Product use	Cellular data	Bluetooth	SD card	SD card
Low/medium volume printing	Batch tray printing	Continuous printing		
Withstand dust	Complete enclosure	Partial enclosure	No enclosure	
Quality control	Imaging	Weight comparison	Manual inspection	
Concepts	High-end solution	Low-end solution	Prusa i3 MK3	

Solutions

This leads to two directions for the design project, a high-end and a low-end solution. The ideal, high-end, solution is illustrated in blue, and can be seen as the envisioned final product. However, to find focus in the project, a lower-end starting point was chosen. This concept is illustrated in orange. Ideally this concept could be upgraded into the ideal solution, if resources allow it. The starting point for this project will be the Prusa i3 MK3, depicted in red.

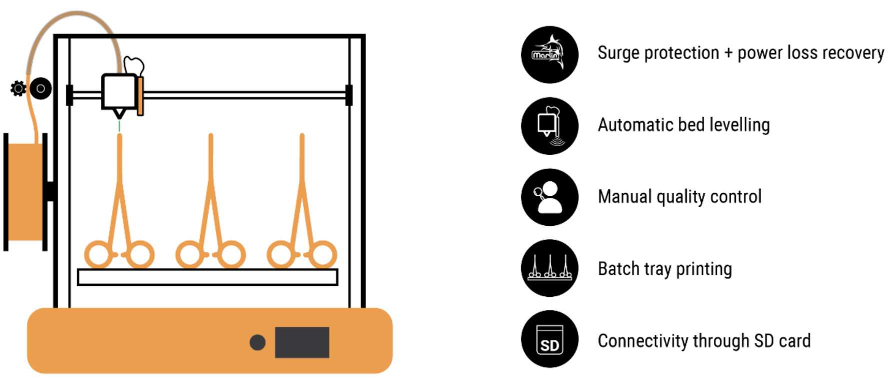
High end - Estimated cost: $ 500

The ideal solution is a cartesian style 3D printer, which utilizes a Bowden Feeder. The printer will be powered by an uninterruptable power supply, meaning it can resume printing for a few minutes in case of a power outage, and is also protected against power surges. In case of a longer outage, prints can be recovered and resumed once the power turns back on. The printer utilizes a continuous printing system, which automatically ejects parts after they are printed. In combination with connectivity through cellular network, this enables the printer to utilize a dynamic printing queue, which can be continuously updated by the hospital personnel. An imaging process ensures that a quality standard is maintained.



Low end - Estimated cost: $ 300

To start off, a simpler, lower end model is envisioned. In case of a power outage the printer will shut down, however, it will recover and resume printing when the power turns back on. This means no prints are lost. The printer will utilize standard batch tray printing, on a stationary heated bed. A similar automated bed levelling procedure is integrated, and the printer is connectable via an SD Card.



Appendix L

Finding correct UPS for 3D printing

Analyzing power consumption Prusa i3 MK3

Luckily many users have documented the power consumption levels of the Prusa i3 MK3 on the Prusa forum [13]. This data will be used for the analysis.

Phase	Power consumption (Watt)
Heatup phase	240
Printing normal	65
Printing heatbed off	50

Calculating required energy storage of UPS:

For simplicity 65 Watts will be used as an average power consumption figure.
This leads to a current of: 65/240 = 0.27 A. The printer needs to run off the grid for 5 minutes, but to take some safety margin into account, 10 minutes will be used for calculations. The amount of energy required in Amp Hours, is therefore: 0.27 * (10/60) = 0.045 Ah. Since the UPS will scale the voltage from 240 to 24V, this leads to a scaling factor of: 240/24 = 10. Multiplying this with the calculated Amp Hours, we get: 0.045 * 10 = 0.45 Ah. Lastly, efficiency of the UPS needs to be taken into account. An efficiency of 80% will be used, resulting in: 0.45/0.8 = 0.56 Ah.

The energy storage of the UPS battery should be at least 0.56 Ah, or 560 mAh. As a reference, most cellphone batteries hold 1000-2000 mAh.

Calculating required VA rating of UPS:

The heatup phase typically draws 240 Watts of power. To be on the safe side, we will use 300 Watt. Usually VA rating multiplied by 0.6 results in true output of Watts of the UPS. Therefore, 300/0.6 = 500 VA, is the minimum rating required for the UPS.

Conclusion

The best fitting machine for these requirements was found to be APC's Black-UPS 500 VA Rating. It is equipped with a battery of 7.2 Ah. This should be able to power the printer off the grid for around 20 minutes, according to the manufacturer. Price of the machine is €65 in the Netherlands, and $ 95 USD in Kenya. This is quite expensive.

Appendix M

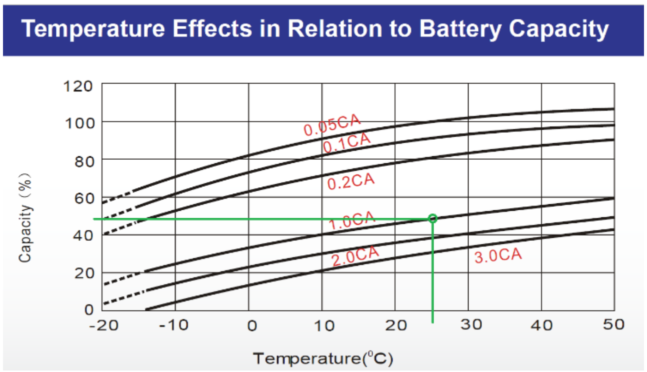
Calculating required battery capacity

A calculation tool was made in Excel to find the minimum battery capacity, based on a method described by PowerStream [14]. The average power drawn by the 3D printer is known, as well as the voltage. This can be used to calculate the average current, with equation 1. The average current multiplied with the total time leads to the required capacity (Ah). However, a lead-acid battery must never be fully discharged below 20% (or lifetime will be greatly shortened). Another thing to take into account is the Peukart Effect, this phenomenon causes the batteries capacity to drop, if it is discharged at a faster rate. The advertised capacity of batteries is usually noted for a discharge time of 20 hours. Since the 3D printer will need to discharge the battery in around 30 minutes, the maximum capacity will be lower than what is advertised by the seller. According to a datasheet from Ultracell [15], a 12V 7Ah battery, being discharged at 1C (7A), will have a 50% capacity. These factors are taken into account in equation 3 to calculate the required capacity of the battery.

Equation 1: $I = P/U$

Equation 2: $C_{required} = I * t$

Equation 3: $C_{battery} = \frac{C_{required}}{C-rate} * \frac{1}{max\ discharge}$



Three battery designs were made, and shown in the table below. For every battery a cost price was estimated based on data found at nkon.nl [16]:

	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

Appendix N

Battery system test

To validate whether it is possible to run a 12V 3D printer on a lead-acid battery system, a test was setup. With this test

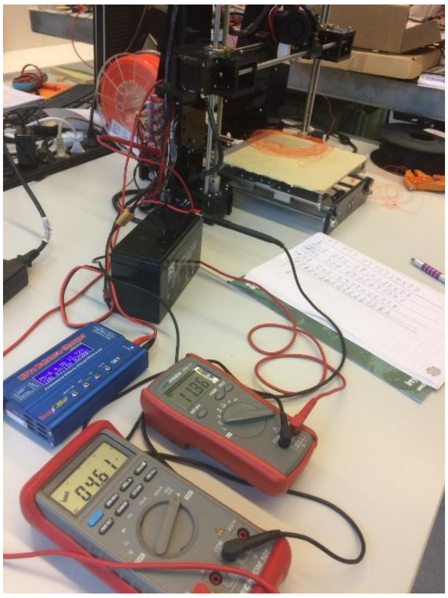
Method

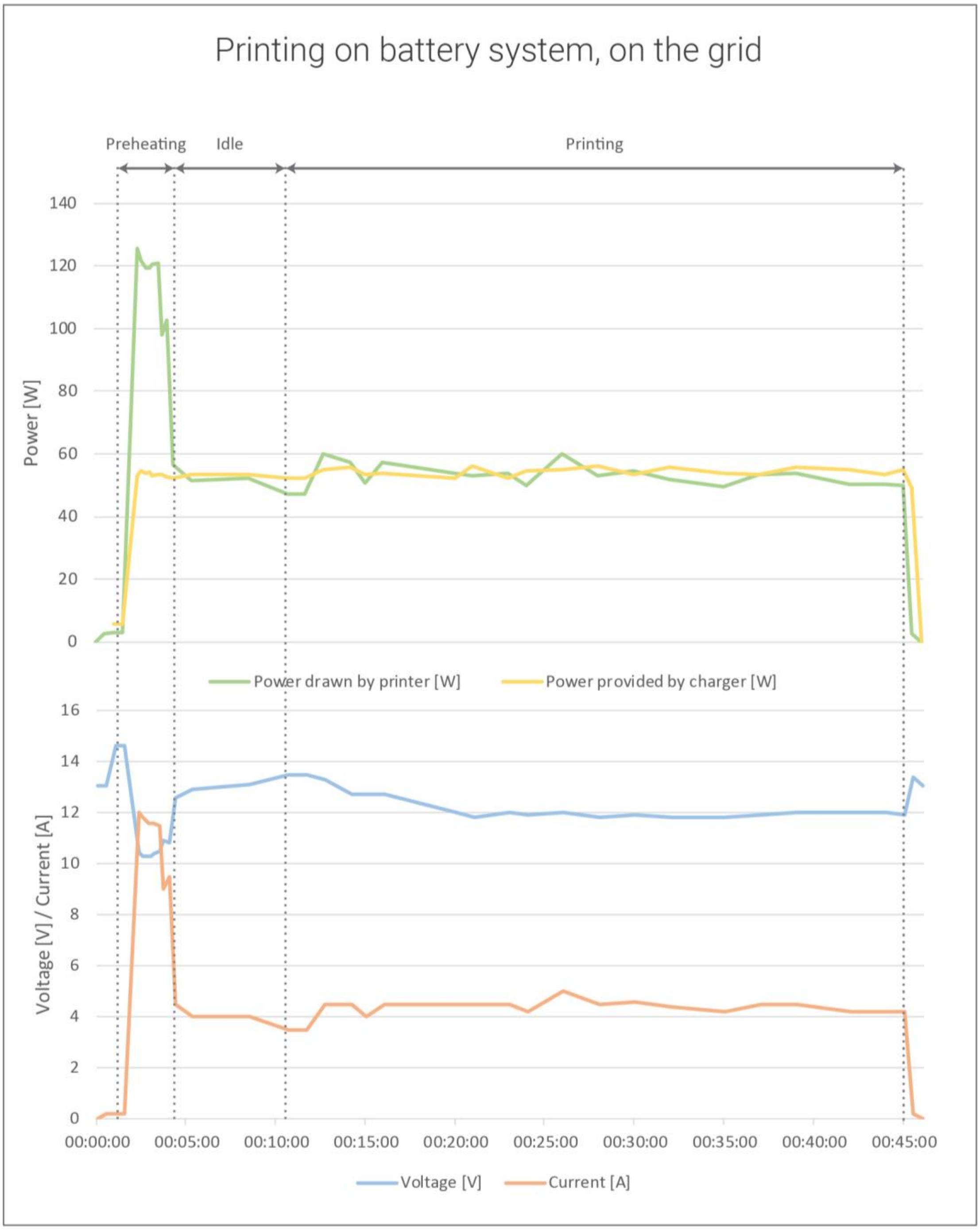
A 12V 7Ah VLRA battery was directly connected to a 12V Anet A6 3D printer. The battery was also connected in parallel to a 12V 5A universal battery charger. In this circuit two multimeters were hooked up, to measure voltages and currents being drawn by the printer. Since the universal battery charger also had a display, this could be read out to view voltages and currents being supplied by the charger.

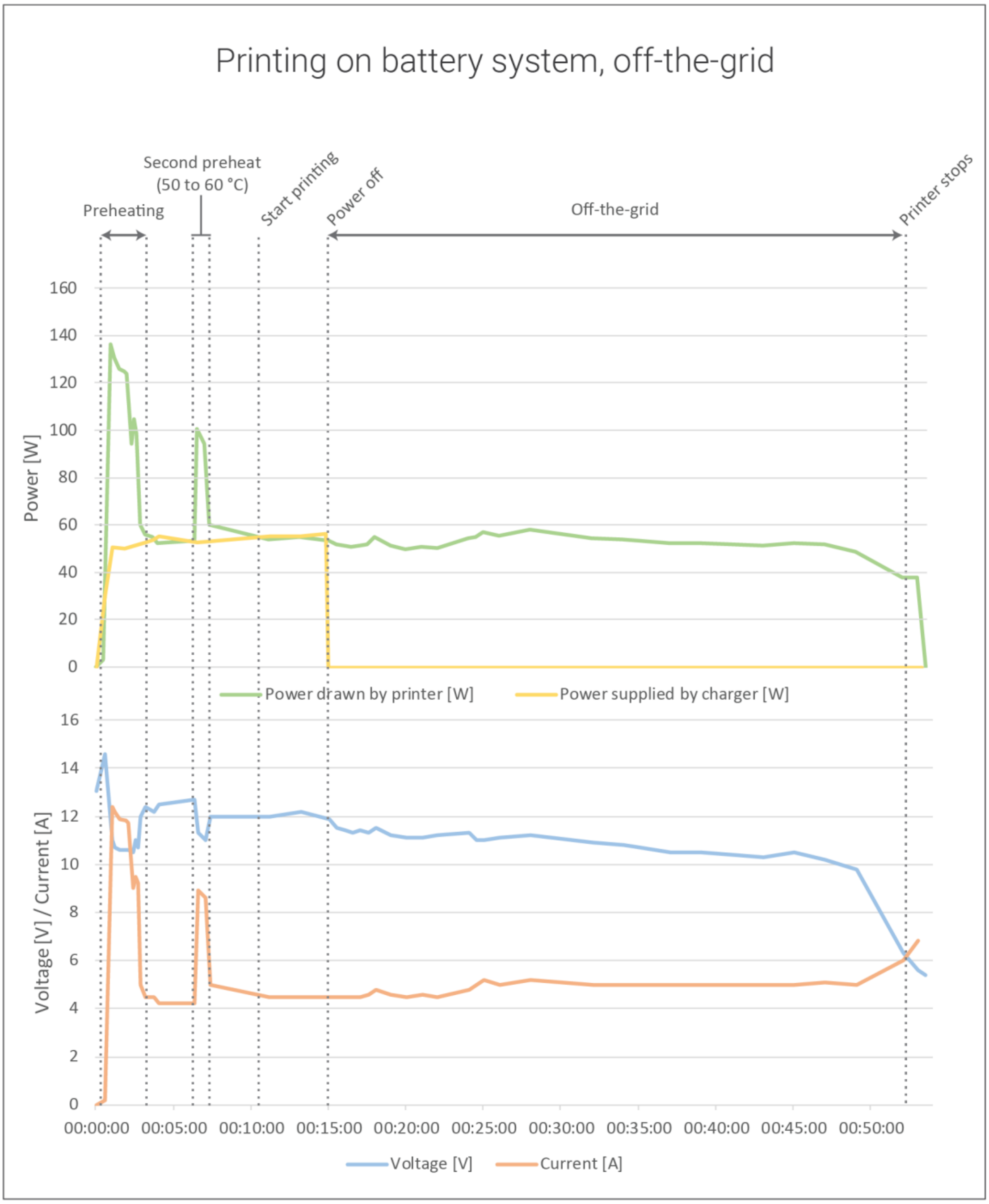
Two tests were devised. First the printer was powered on the battery system, while being connected to the grid, and a 30 minute print job was started. This procedure was repeated, but this time, the plug was pulled on the charger after 15 minutes.

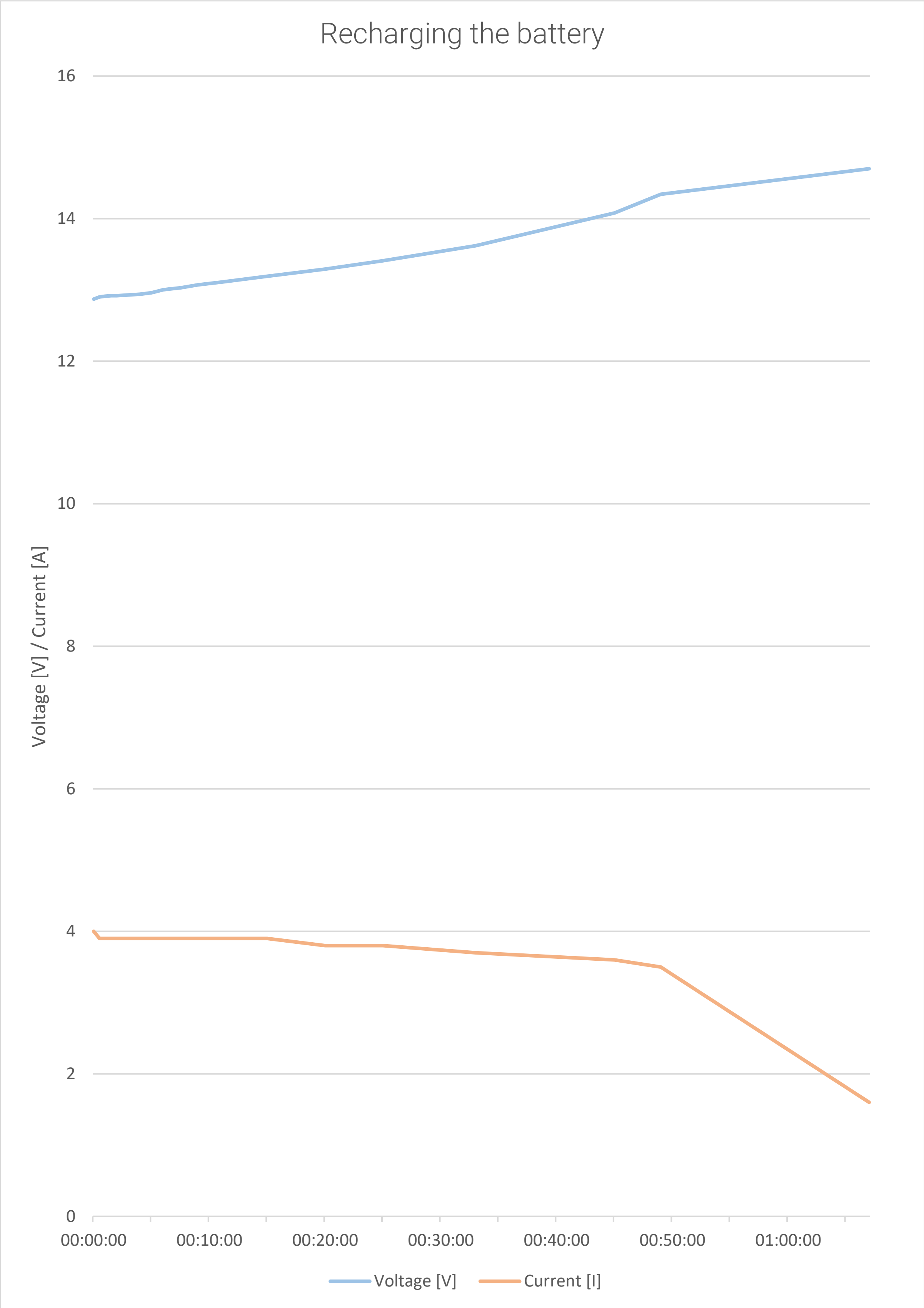
Results

During both these tests the voltages and currents shown by the multimeters and smart charger were continuously noted. This data was used to make several graphs, which can be viewed below.




Printing on battery system, on the grid
Preheating
Idle
Printing
Power [W]
140
120
100
80
60
40
20
0
Power drawn by printer [W]
Power provided by charger [W]
Voltage [V] / Current [A]
16
14
12
10
8
6
4
2
0
00:00:00
00:05:00
00:10:00
00:15:00
00:20:00
00:25:00
00:30:00
00:35:00
00:40:00
00:45:00
Voltage [V]
Current [A]


Printing on battery system, off-the-grid
Second preheat
(50 to 60 °C)
Preheating
Start printing
Power off
Off-the-grid
Printer stops
Power [W]
160
140
120
100
80
60
40
20
0
Power drawn by printer [W]
Power supplied by charger [W]
Voltage [V] / Current [A]
16
14
12
10
8
6
4
2
0
00:00:00
00:05:00
00:10:00
00:15:00
00:20:00
00:25:00
00:30:00
00:35:00
00:40:00
00:45:00
00:50:00
Voltage [V]
Current [A]


Recharging the battery
16
14
12
10
8
6
4
2
0
Voltage [V] / Current [A]
00:00:00
00:10:00
00:20:00
00:30:00
00:40:00
00:50:00
01:00:00
Voltage [V]
Current [I]

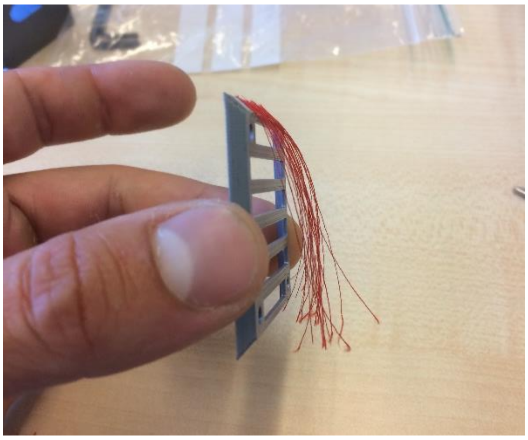
Appendix O

Dust filter air flow tests

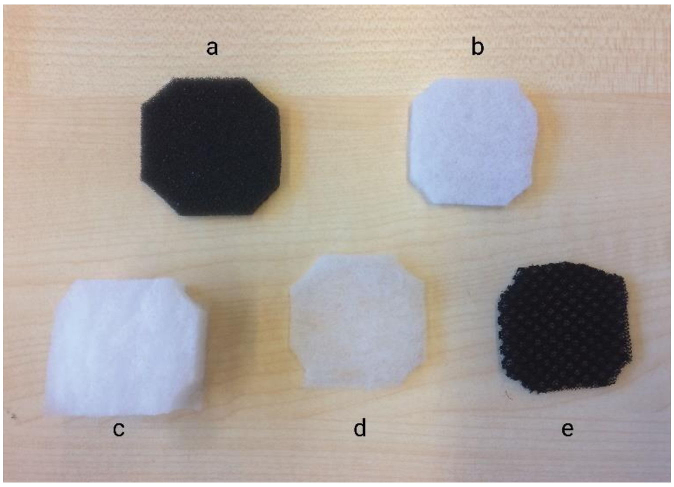
To test the air flow produced by the fan through different dust filters, a simple test had to be devised.

Method

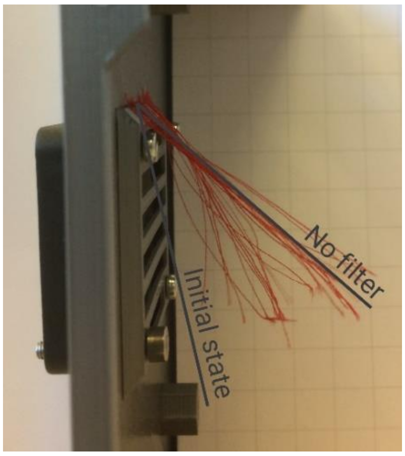
In this test, threads of fine red fabric were attached to the dust filter guard in front of the fan. This makes it possible to visualize air flow; the higher the threads rise, the better the air flow.



With this method five different dust filters were tested for air flow, as shown in figure fixme.



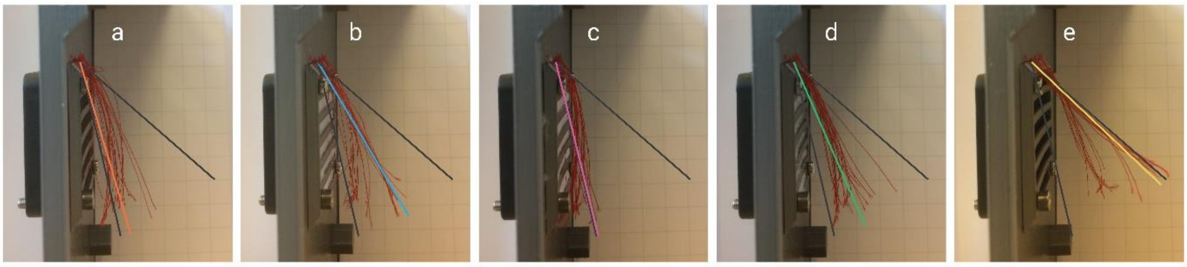
a=Philips spongefilter [17], b=Scanpart microfilter [18], c=Professional M5 filter [19], d=1/5th thickness professional M5 filter [19], e=mesh material that was lying around the workspace.

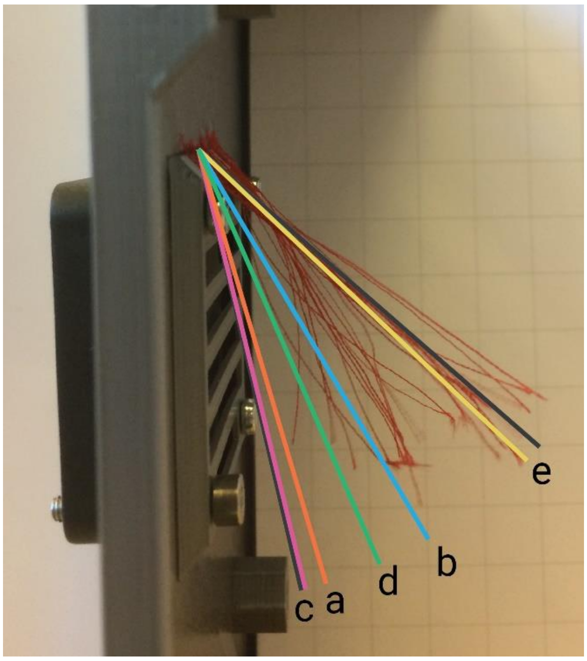


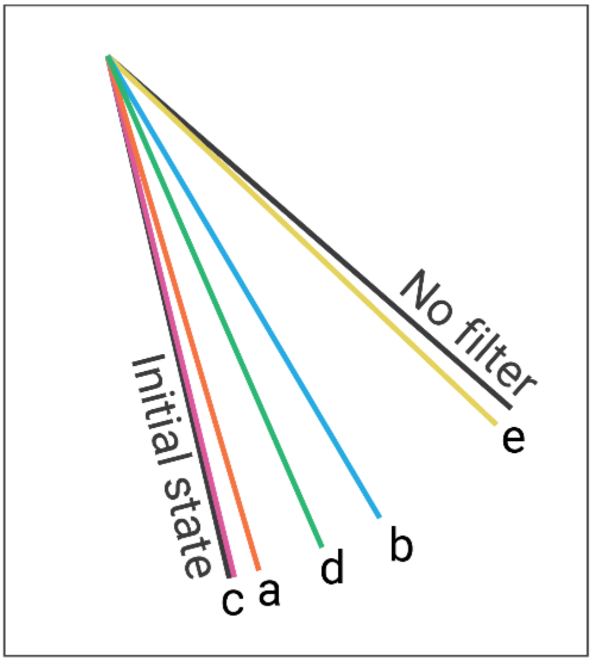
When the fan was turned off, the threads hung down, and this was noted as the initial state. When the fan was turned on, without any dust filter, the threads rose highest, and this was noted as the no filter state. See figure below.

Results

The results of the airflow visualizations for every dust filter are shown in the figure below. For every filter, a trendline was drawn along the direction of the largest amount of threads. These lines were added together in figure below, to give an overview of the air flow for every dust filter in relation to each other.







Conclusion

As can be seen above, material e allowed for the best air flow. This was in line with expectations, as this mesh material is very porous. The same fact is also why it is not regarded as an ideal filter; dust can pass through too easily. The most effective filter against dust is material c. Unfortunately, this material blocked virtually all airflow, and is therefore not suitable. Material b however, is normally used as a dust filter in vacuum cleaners. Its tightly bundled structure makes it ideal for catching fine dust particles, and as shown above, it also allows for decent airflow, this is regarded the optimal solution.

Appendix P

Enclosure Ingress Protection Test

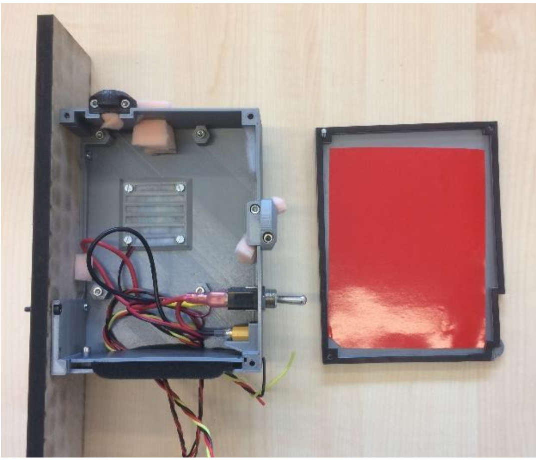
One of the requirements for the enclosure is to make sure it meets an IP5 rating. IP5 means "Ingress of dust is not entirely prevented, but it must not enter in sufficient quantity to interfere with the satisfactory operation of the equipment" [20]. This definition is quite vague and unquantifiable. However, more insights can be extracted from the test method that the industry uses. For an IP5 rating, this involves exposing the enclosure to fine-grained talcum powder in a dust chamber for 2 to 8 hours [21]. If no dust was able to enter the enclosure, it will be awarded an IP5 rating.

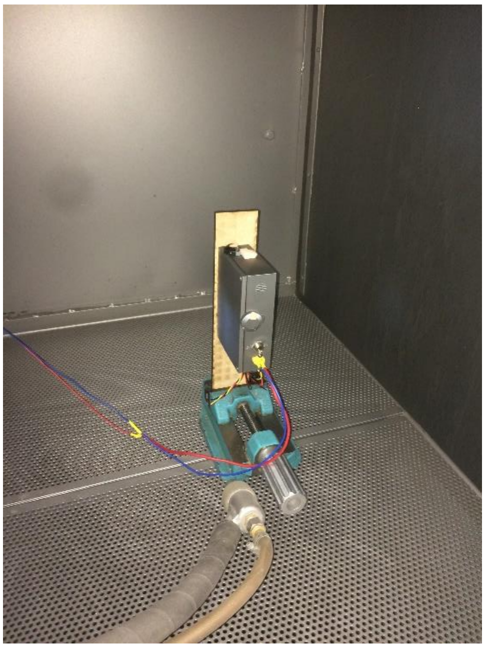
Method

A similar test was devised, in which a sand blasting machine was used to function as a dust chamber. According to employees of the workshop, the sandblasting machine circulates fine glass beads around the chamber, which bounce of the walls and break into smaller particles. This way a range of different sized particles circulate the chamber, ranging from fine dust, to sand grain size beads.

The electronics enclosure was attached to a piece of wood, which replaces the function of the frame. All holes where cables run through were sealed with dense foam. On the inside of the lid a sheet of sticking red nylon was attached, to catch entering dust particles, and make them visually noticeable.

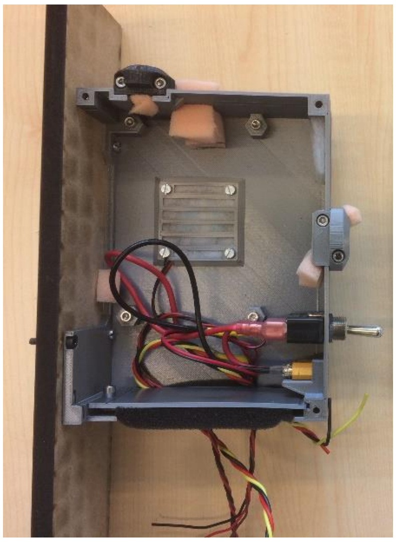
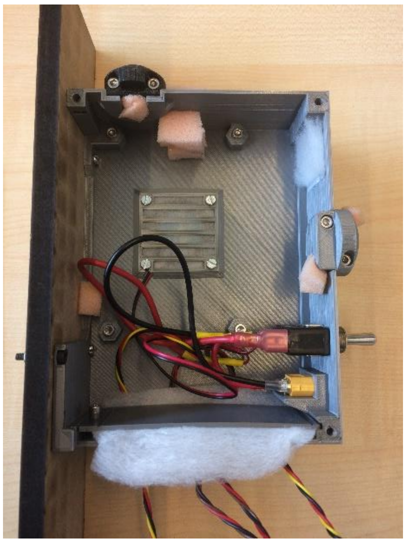
During testing, the enclosure's fan was turned on. Every test was run for one hour, and the air pressure for set to the maximum of 4 bar.



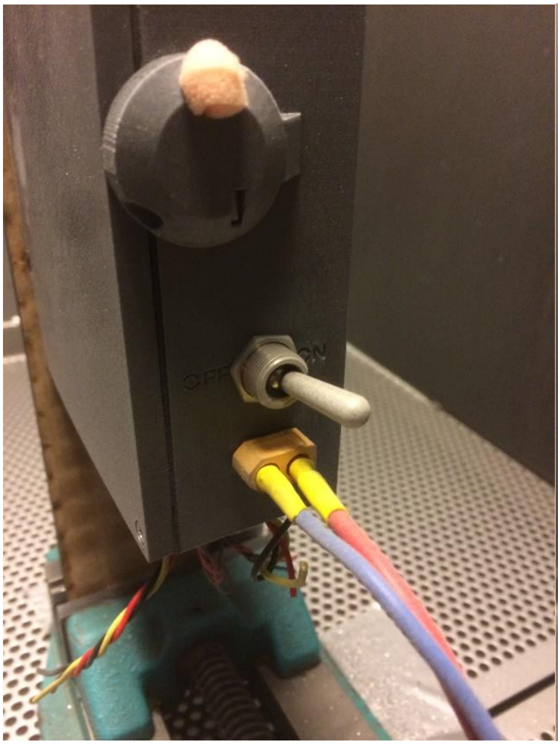
The test was repeated three times, to compare different sealing methods for the bottom cables:

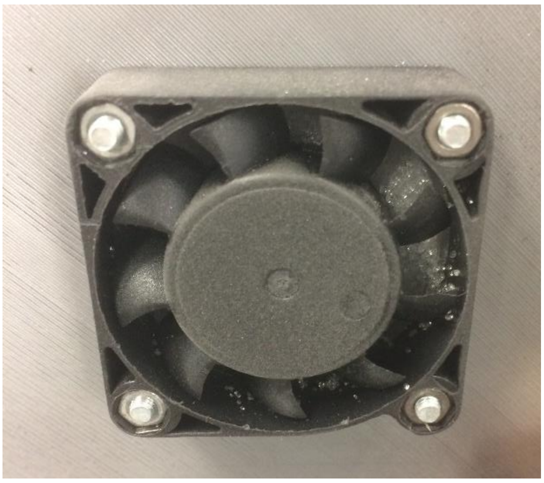
1. Using 10mm thick Philips spongefilter [17] (left)
2. Using 20mm thick Professional M5 filter [19] (middle)
3. Using duct tape (right)

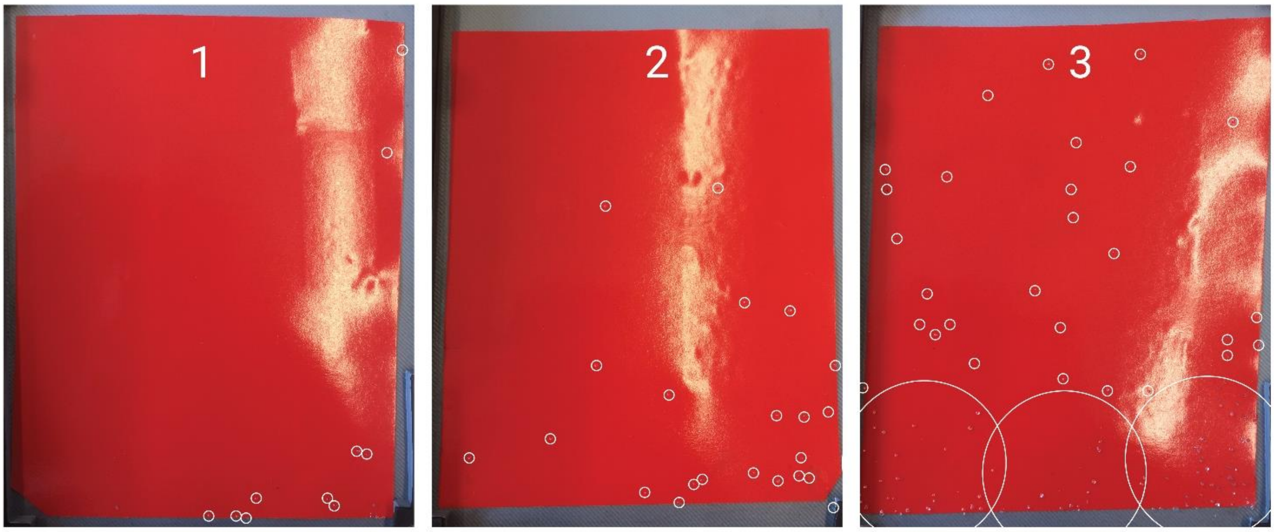

Results

After every test, the enclosure was covered in a thin layer of very fine dust, as can be seen on the pictures below. The fan had accumulated many of the glass beads.





The amount of dust captured for each of the three tests is shown on the image below.



Conclusion

In all three tests most of the particles collected in the bottom right corner, which was in line with expectations, as this is a weakest part of the seal of the enclosure. Surprisingly, the duct tape seal (number 3) was least effective. It appears that the 10mm thick black sponge filter was most effective against stopping dust from entering from the bottom. A more general insight that can be concluded, is that the enclosure was not sealed enough to stop small particles from entering, as even the sand grain sized glass beads managed to get in with every test. The dust filters do seem to be working properly, as almost no dust was collected in the middle of the red sheet.

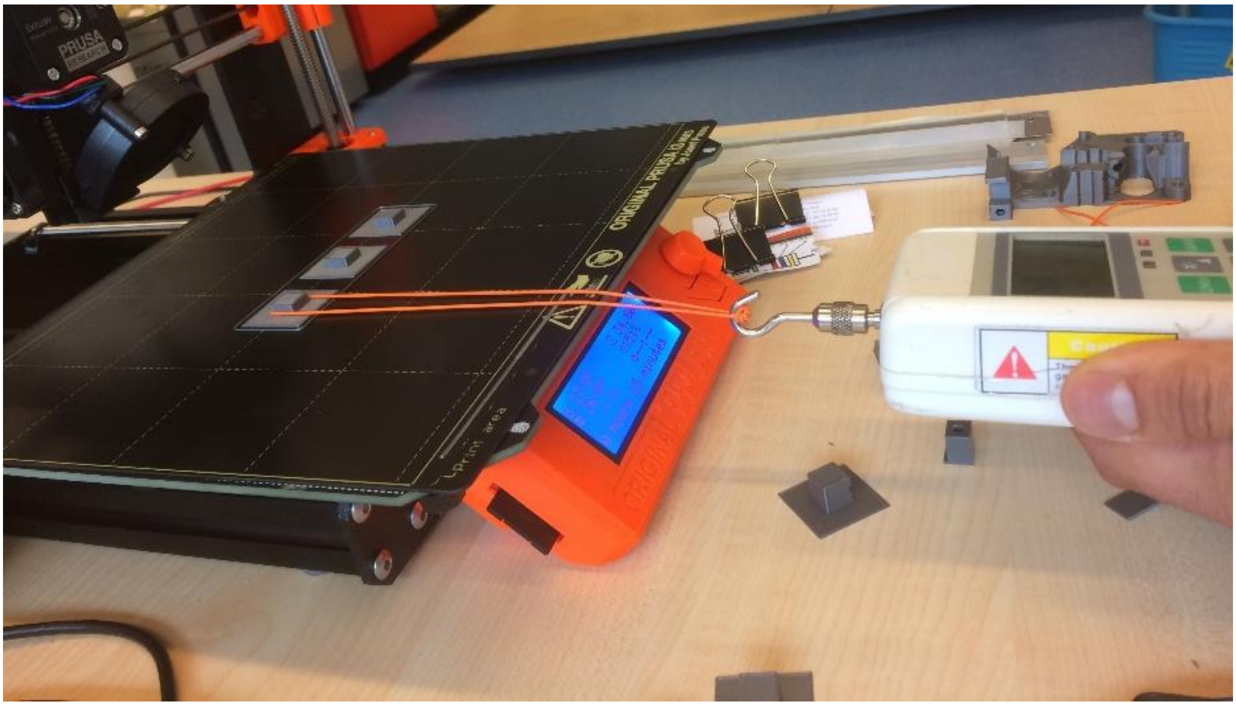
Appendix Q

Bed adhesion test

A test was devised to measure the difference in bed adhesion between Prusa's conventional PEI coated bed, and the Ultrabase bed from Anycubic [22]. It was hypothesized that the Ultrabase bed would allow parts to be removed easier after cooling. Moreover, it was hypothesized that cooling down the bed actively, with the help of blower fans, would make it even easier to dislodge parts.

Method

Three test cubes (20x20mm) were printed with a large raft (40x40mm). The bed was cooled, either actively by using two fans (see figure Fixme), or passively. The parts were dislodged by pulling them off the bed with an steel wire attached to a force meter. The values returned by the force meter were recorded to evaluate the force needed to dislodge the part. This test was performed with the conventional PEI coated bed, and with the Ultrabase bed.



The test was repeated four times, according to the following:

1. Conventional PEI coated bed, passive cooldown
2. Conventional PEI coated bed, active cooldown
3. Ultrabase bed, passive cooldown
4. Ultrabase bed, active cooldown

Results

Test 1: Conventional PEI bed, passive cooldown

Sample	Force (N)
1	56
2	> 80
3	> 80

Test 2: Conventional PEI bed, active cooldown

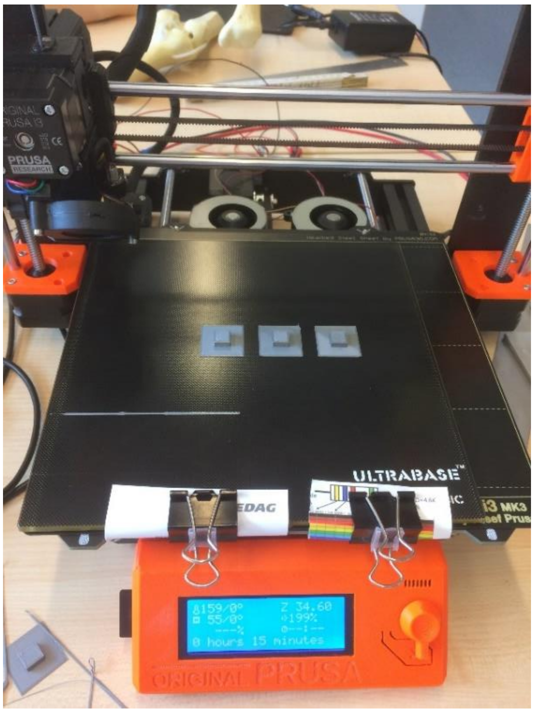
Sample	Force (N)
1	50
2	> 80
3	52

Test 3: Ultrabase bed, passive cooldown

Sample	Force (N)
1	46
2	44
3	2

Test 4: Ultrabase bed, active cooldown

Sample	Force (N)
1	18
2	15
3	2



While testing the PEI bed, several times the part was stuck to the bed so well that the force to pull it off exceeded 80N (which is the limit of the force meter). The parts had to be removed with a scraper. It is clear that switching to the Ultrabase resulted in much easier part dislodging. Another interesting insight is that cooling the bed down faster results in even lower forces needed to dislodge the part (see test 4).

In a similar way, the maximum force that the motors can supply until stalling was tested. This turned out to be 28.8N, regardless whether the printer was in stealth or normal mode.

Another observation made during this test was that when the ultrabase bed was cooled fast, it was possible to hear cracking sounds, as the bottom layer was breaking loose from the bed.

Conclusion

It is safe to say that the Ultrabase bed provides much easier part removal, with dislodge forces being on average twice as low than with the conventional PEI bed. Moreover, active cooling shows to further increase ease of dislodging. This effect is noticeable mostly with the Ultrabase bed, as parts are dislodged twice as easily. The forces required to remove the parts with this strategy are below the maximum force that the motor can generate (18N vs 28.8N), a very promising result.

Appendix R

Active cooling system test

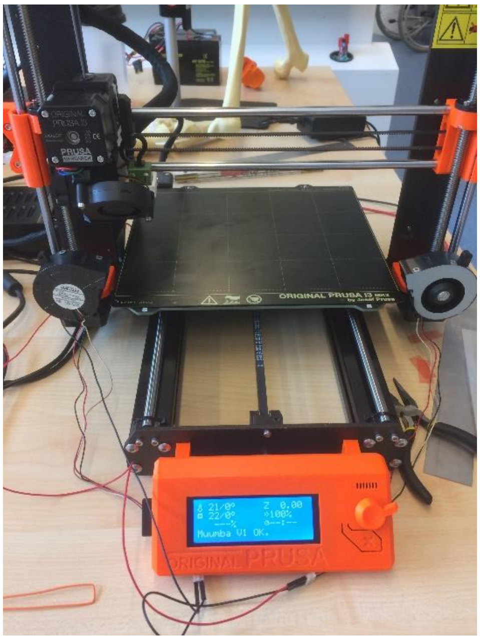
It was found that blowing air directly onto the print bed with two (12V) projector fans was the most effective way to cool the bed. In this test, different placements of the fans were tested to find the setup that could cool the bed most effectively.

Method

To find the most appropriate placement, four tests were performed:

1. No fans
2. Fans placed under the bed
3. Fans placed on top of the bed
4. Fans placed on the sides of the bed

In all of these tests the temperature was measured over time by reading out the thermistor values of the bed thermistor. These tests were performed **without the glass bed.**

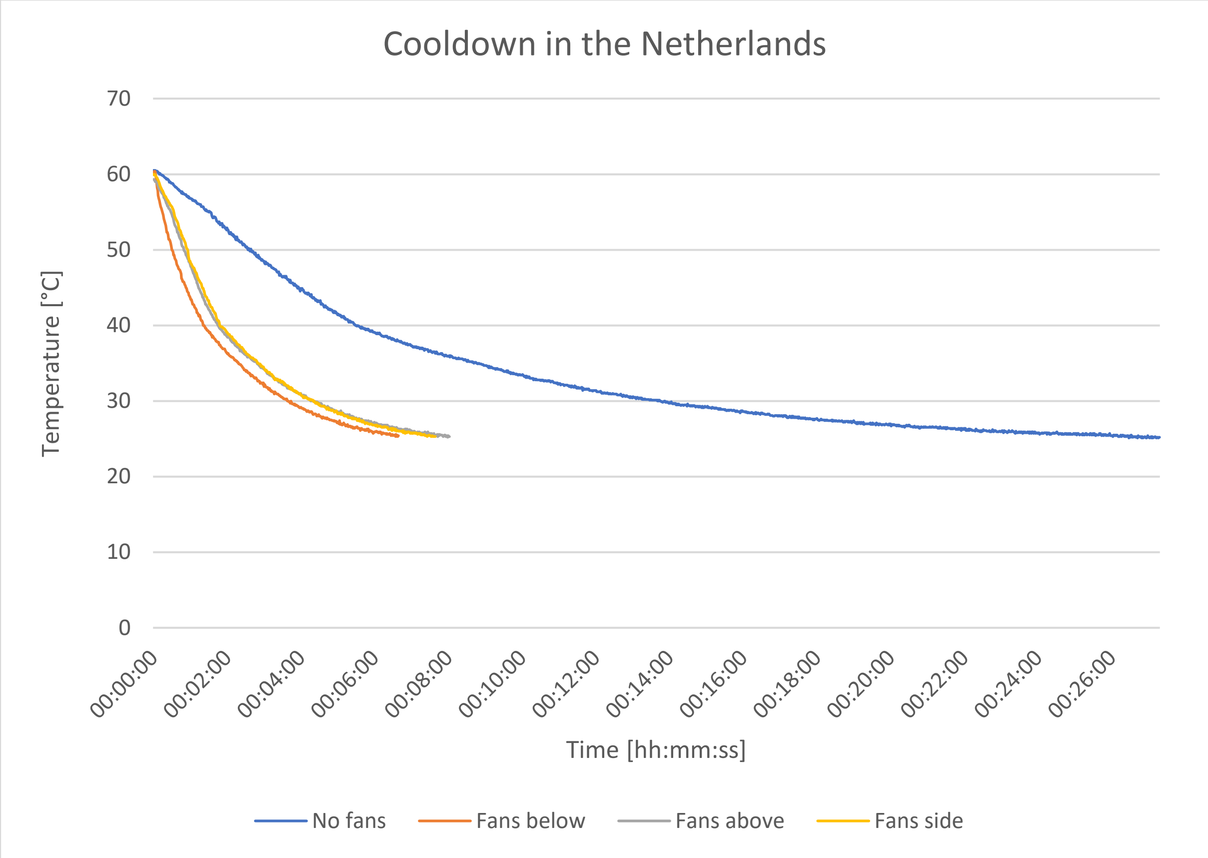


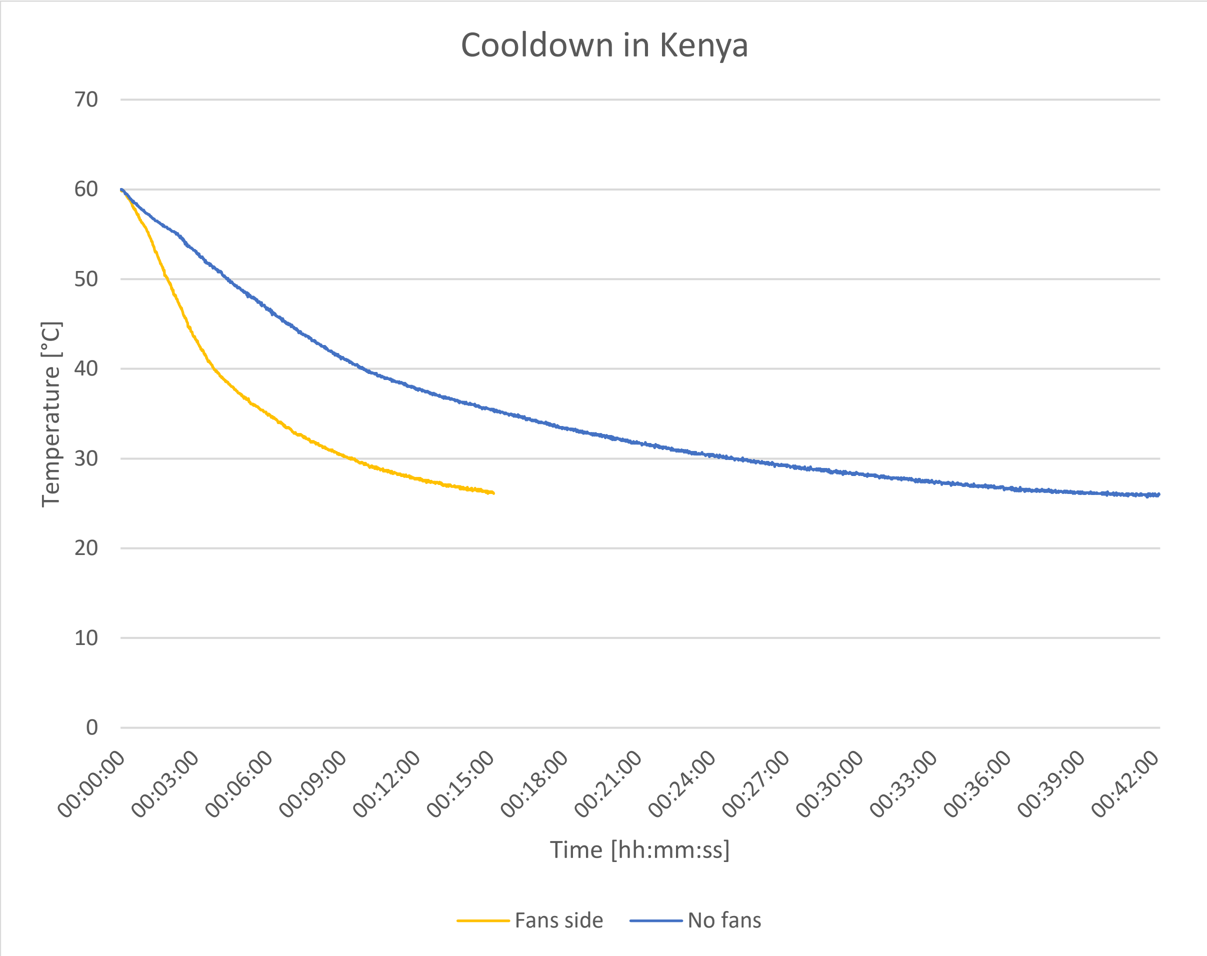
Results

Ambient temperature was 21 °C. Time to cool down the bed from 60 to 25 °C:

1. No fans: 27.3 min
2. Fans placed under the bed: 6.7 min
3. Fans placed on top of the bed: 8.1 min
4. Fans placed on the sides of the bed: 7.7 min

This is also indicated in the graph show in figure Fixme. The same test was also conducted in Kenya, where ambient temperatures were around 25 °C. Similar results were found, except that cooling took almost twice as long: 15 minutes for fans on the side and 42 minutes for no fans.

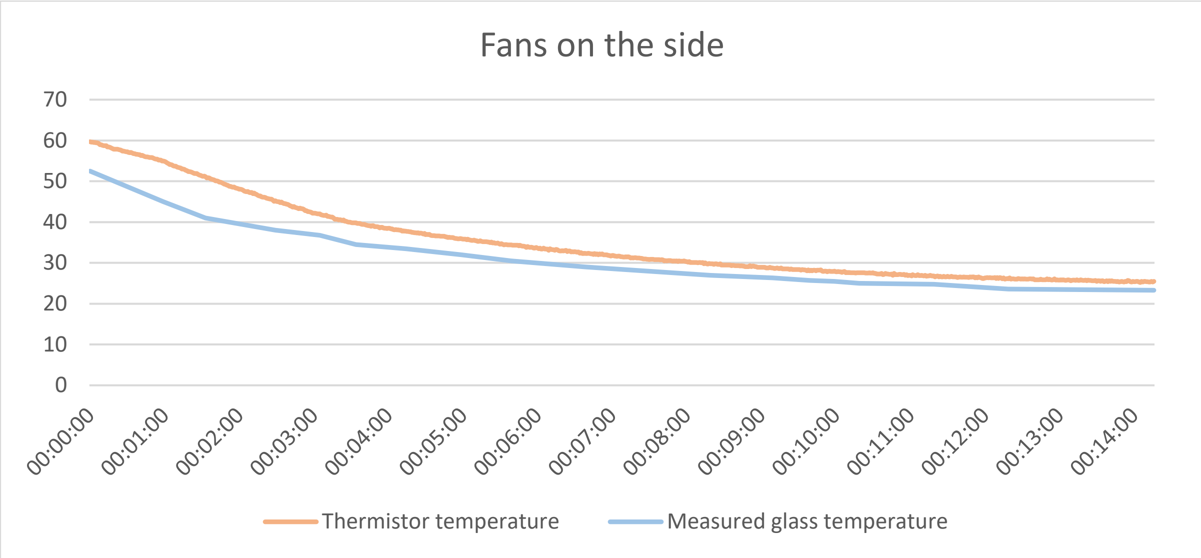

Cooldown in the Netherlands
Temperature [°C]
70
60
50
40
30
20
10
0
00:00:00
00:02:00
00:04:00
00:06:00
00:08:00
00:10:00
00:12:00
00:14:00
00:16:00
00:18:00
00:20:00
00:22:00
00:24:00
00:26:00
Time [hh:mm:ss]
No fans
Fans below
Fans above
Fans side



From these results one could conclude that the best strategy would be to place the fans under the bed. However, it was hypothesized that with the glass bed added on top, there would be a temperature difference between the top of the glass, and the bottom of the hot bed (where the thermistor is reading the temperature). Moreover, it was hypothesized that cooling the bed from underneath would be more effective for the readings from the thermistor, but might be less effective for the actual temperature of the top of the glass bed.

To test these hypothesis, a second test was performed, where the temperature of the glass was measured with a temperature measurement gun and compared with the thermistor temperature. This test was done for both the setup with fans under the bed, and the setup with fans on the sides of the bed. This resulted in the following data:

	Fans under the bed	Fans on the side
Time to cool bottom of bed (thermistor)	11.8 min	14.3 min
Time to cool glass (measurement)	12.3 min	10.3 min



This shows that indeed, cooling the bed from the side cools down the top of the bed faster, than cooling the bed from underneath, which does cool down the bottom faster.

Conclusion

It appears that the bottom of the bed cools fastest when the fans are placed at the bottom, and the top of the bed cools fastest when the fans are placed at the side. The best strategy is to place the fans on the side, as the top layer of the glass should be cooled fastest. Another interesting finding is that cooling the bed in Kenya took almost twice as long, even when active cooling with fans was used. Ambient temperatures were around 25 degrees, and the climate is much more humid.

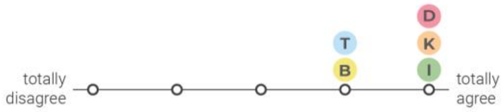
Appendix S

Evaluation questionnaire

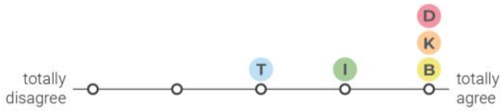
The results of the questionnaire have been collected in a structured overview. All of the experts have been given their own bullet point. This makes it easy to see who answered what.

- Derrick
- Karl
- Ishmael
- Tobias
- Ben

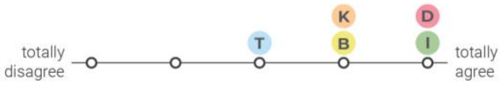
1. General



1.1 Do you think the found design challenges accurately cover the problems of 3D printing in Kenya?

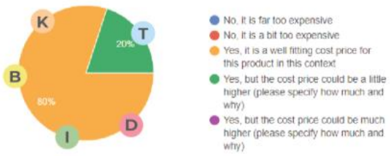


1.2 Do you think the defined design drivers form a fitting design strategy to the context?

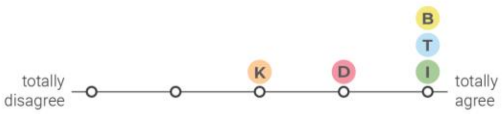


1.3 Do you think the list of requirements is complete and adequate for this product in this context?

2. The final design proposal



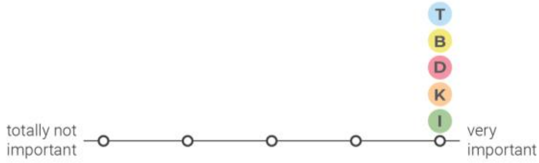
2.1 Do you think the final cost price fits the context?



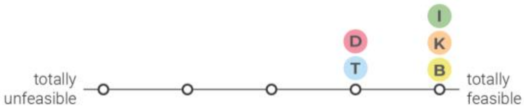
2.2 Do you think the RepRap Prusa i3 design is a good foundation for this 3D printer?

3. Ability to operate on an unstable grid

3.1 How well does this solution tackle the challenge?



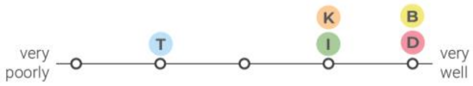
3.2 How important do you think this solution is?



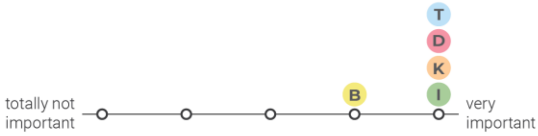
3.3 How feasible do you think this solution is?

3.4 How well does this solution address the values and needs of the context and user?

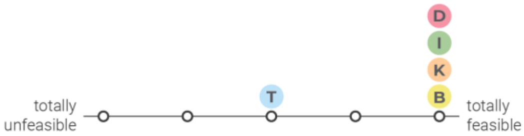
4. Dust filter



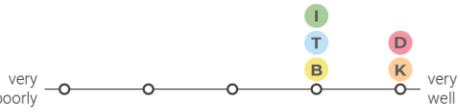
4.1 How well does this solution tackle the challenge?



4.2 How important do you think this solution is?



4.3 How feasible do you think this solution is?



4.4 How well does this solution address the values and needs of the context and user?

5. Electronics enclosure

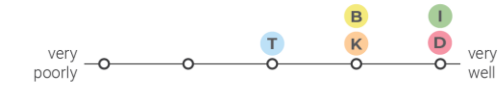
5.1 How well does this solution tackle the challenge?

5.2 How important do you think this solution is?

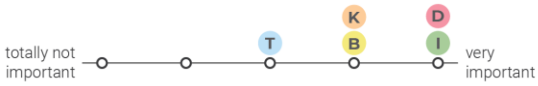
5.3 How feasible do you think this solution is?

5.4 How well does this solution address the values and needs of the context and user?

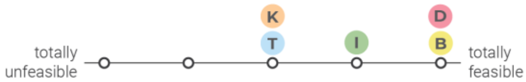
6. Continuous printing



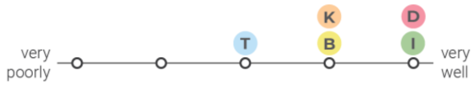
6.1 How well does this solution tackle the challenge?



6.2 How important do you think this solution is?

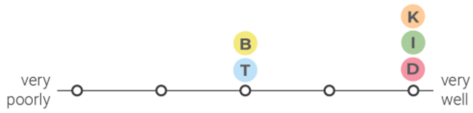


6.3 How feasible do you think this solution is?

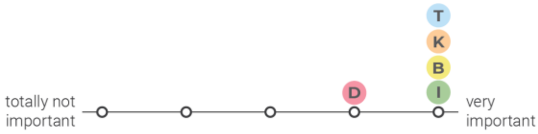


6.4 How well does this solution address the values and needs of the context and user?

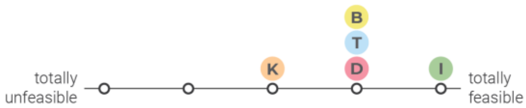
7. Connectivity & use



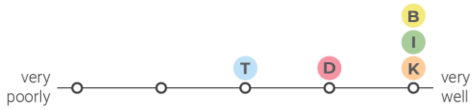
7.1 How well does this solution tackle the challenge?



7.2 How important do you think this solution is?

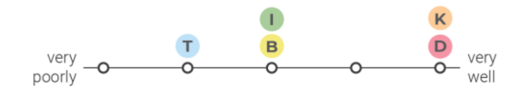


7.3 How feasible do you think this solution is?

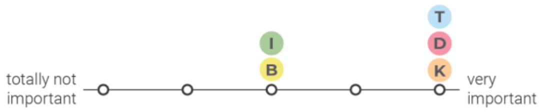


7.4 How well does this solution address the values and needs of the context and user?

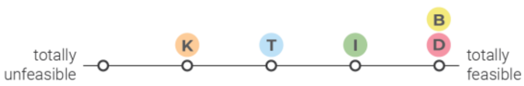
8. Transportability



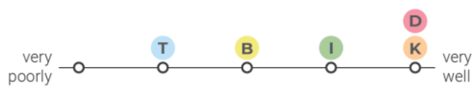
8.1 How well does this solution tackle the challenge?



8.2 How important do you think this solution is?

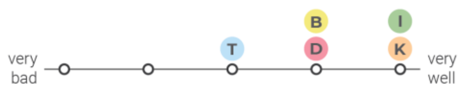


8.3 How feasible do you think this solution is?

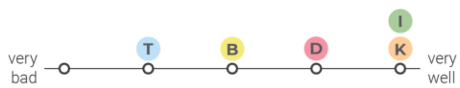


8.4 How well does this solution address the values and needs of the context and user?

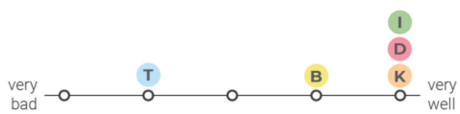
9. Final evaluation



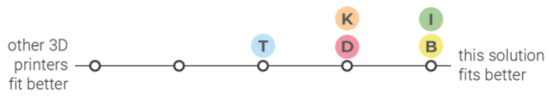
9.1 How well do you think this final design proposal fits to the context? (of Kenya)



9.2 How well do you think this final design proposal fits to the intended usage (producing medical equipment)?



9.3 How well do you think this final design proposal fits to the intended user? (Local entrepreneurs and business owners)



9.4 How well does the final design fit the intended context, user and use, in comparison to current 3D printers on the market?

Answers to open questions

1. General

1.1 Do you think the found design challenges accurately cover the problems of 3D printing in Kenya?

Ben
I think there is still more to be done on design challenge #4 (Usability). Not that this current design is not usable, but there is not enough data out there to yet to sufficiently define these criteria.

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

1.2 Do you think the defined design drivers form a fitting design strategy to the context?

Ben
While there are plenty of design drivers for 3D printing beyond these 3, I think you have successfully identified the drivers that are needed for 3D printing to be successful in these contexts.

Tobias
Serviceability and/or upgradability to prevent obsolescence.

1.3 Do you think the list of requirements is complete and adequate for this product in this context?

Derrick
Other than the electronics there could be a need to add a full enclosure for the device to make it dust proof and easy to clean especially for a hospital setup

Karl
With the printer set at a market price of $800, one has got to deliver a 3D printer that communicates not just great value proposition but also an experience.

Ben
These requirements are definitely adequate! However, there are plenty more that could also be introduced in the future. In addition to usability requirements (which, again, no one has quantified yet), there are several healthcare-specific requirements that are not yet accounted for (sterility, non-toxic, etc.), and some of the requirements could use more specificity in the future.

Tobias
Include requirements for safety, both for the printer and the printed parts. If considering parts for healthcare in Kenya, material safety concerns are important.

2. The final design proposal

2.1 Do you think the final cost price fits the context?

Karl
From a European context if you were to buy a 3D printer at this price point with value proposition will you communicate? What will be the experience derived? I believe the cost price is might sound slightly expensive, however if the experience derived is greater than the current state (print quality, durability, ease of repair,etc) then the market price will be valid.

Ben
Assuming that the printer is going to be purchased by a local entrepreneur, this seems to be in the appropriate cost-range, based on our past experiences. However, there are some entrepreneurs who may be willing to pay more.

Ishmael
This will be determined by the size of the prints

Tobias
Including filament sensors and additional thermistors could increase usability of design.

2.2 Do you think the RepRap Prusa i3 design is a good foundation for this 3D printer?

Karl
I think the RepRap prusa i3 design is ok. How could we make this design contextualized to a brand that the Kenya 3D ecosystem will love to make it their own.

Ben
Based on our experiences, the Prusa designs are among the most-reliable in the <$1000 category, and if we had it to do over again, we absolutely would have made our design around the Prusa. I think its relative simplicity and open-source nature make it a good candidate for this project.

Ishmael
Small enough to move around with and cheap too

Tobias
Continuing improvements by Prusa research could be incorporated

3. Ability to operate on an unstable grid

Karl
Power fluctuation is a menace that the Kenya locals resonates with. This means one has got to really on steady power that can guarantee a print.

Ben
I think this solution makes perfect sense, and our test users have continually ranked power issues among their largest concerns. I think 1 hr is the perfect amount of time for users based in town, especially if the battery is coupled with the ability to resume prints. Users in more rural areas, however, may need longer battery options (something to consider in future designs). I am curious, did you do any power-failure testing with this power-source? I ask because even a brief flicker can throw off a 3D print, and I am curious if there is data on how it performed.

Tobias
Understanding the effect of feedback on operators is important, wireless monitoring of power supply by manufacturer may be implemented for improved maintenance scheduling

4. Dust filter

Ben
Great solution. I am assuming the user will need to clean this periodically?

Tobias
Dust corroding other components in the printer, such as the rails and bearings, is not addressed by this solution. An amount of dust may still be introduced during filament retraction, which is not addressed

5. Electronics enclosure

Karl
Hope the fan used in the system can be purchased/repaired locally. If not we need a system of how we get spares.

Ben
Great solution to protecting the electronics. My only concern was over overheating, but your data clears up that concern quite easily!

Ishmael
The casing would help protect the electronics from damage and direct contact with user

6. Continuous printing

Karl
I think this feature, needs to be exploited more on feasible it is.

Ben
I enjoyed the video, and I think this is a great solution. Many multi-print plates end up failing one part or the other, so I am glad this does one at a time. I forget, however, can the gcode change in between prints automatically or does that software not exist yet (I think that will be an important feature). My other potential concern would just be on how this affects reliability of

prints. If a part is poorly sliced and the user just sets it and lets it go, it could result in a lot of wasted material. Again, minor concerns. I think this is a great solution.

Ishmael
continuous printing will depend on which part if the unit(hospital set up) as well as the mind set of the nurses/doctors operating at the area

Tobias
Removing the operator in this difficult context requires automated inspection and process control. Intervention required to remove part also allows for assessment of quality and adjustment of hardware. I would be worried about many poorly printed parts while the operator is not watching.

7. Connectivity & use

Karl
How feasible is this taking into consideration that card files may change and needs to be sliced before printing?

Ben
I like this overall solution, and we have worked towards it in the past. I think its a great overall strategy, but there may be unforeseen challenges when working out the details of the software/hardware interface. I look forward to seeing more development in this area of the field. (Also, the idea of usability creeps in again here, both in terms of understanding user and phone limitations).

Tobias
Ordering appears to be addressed, but operation and maintenance is not

8. Transportability

Karl
So if someone disassemble the printer, are they able to put it back together? Do you need a highly specialized skill to assemble the printer? How do you make this experience fun and enjoying and not frustrating and disappointing experience. You must know how much work goes into disassembling an assembling a 3D printer.

Ben
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). I suspect this design feature is one that has widely different value depending on who is using the 3D printer. Some users may be relatively stationary, and may care about portability less than others. Our research team though, for example, put it as a high priority.

Ishmael
most of the working printer would be require to be at one place
most nurses/doctors and operators would prefer not movable once assembled and operational

Tobias
The unpacked printer will be damaged in transportation. Please consider specific packaging to protect printer during shipping

9. Final evaluation

Ben
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!

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

Appendix T

Updated list of requirements

Group	#	Type	Description
General	1.1	Req	The printer should be able to produce parts with a maximum tolerance of ±0.5mm
	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 acompanied 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 µm (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 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)
Safety	10.1	Req	The printer should not pose any toxic safety hazards
	10.2	Req	Every touchable edge of the printer should have a minimum radius of 1 mm
	10.3	Req	No body parts can get stuck when using the prodct
Medical	11.1	Req	The printer should be able to produce sterile equipment
	11.2	Req	The printer should be able to produce non-toxic parts
	11.3	Req	The printer should be able to produce biocompatible parts

Appendix U

Business model canvas

Vision

Everyone should have access to proper healthcare.

By making 3D printing accessible in low resource countries a new type of local manufacturing can emerge, enabling the local production of basic but essential medical equipment for a fraction of the cost, and greatly reduced lead times.

Partners

- Kijenzi (Penn State University), develops and maintains the platform from which hospitals and others can order parts from 3D printer entrepreneurs. They also continuously design and develop new parts that can be 3D printed, and addd these to their catalogue.
- Government of Kenya. They can subsidise the production and distribution of the printers. (e.g. by lowering taxes)

Activities

- Produce and assemble 3D printers in Kenya
- Educate entrepreneurs to become 3D printer operators
- Provide technical support and maintenance of the 3D printers out in the field
- Sell plastic filament to 3D printer operators (and others)
- Promote/market the business opportunity of starting a 3D printing business for hospitals and others

Resources

- Local suppliers providing components
- Local employees building 3D printers
- Partners in China that can ship specialty 3D printing parts

Value proposition

- Is able to function on a grid with frequent power outages
- Can deal with excessive dust
- Is easy to operate by anyone
- High productivity due to automatic part ejection
- Very competitively priced due to locally sourced parts

Relationships

There will be close contact between us and the customers. After they buy a 3D printer, we will train them in how to use it, and how they can set up their mini factory to start producing parts. After that we will be available for technical support and assistance. Moreover, we will remain their partner in providing them with 3D printing materials.

Channels

The 3D printer entrepreneurs can be reached through word of mouth, and social media advertising. Kenyans have a highly entrepreneurial mindset, and therefor an interesting new business opportunity should greatly appeal to them. Hospitals and other organizations can be contacted directly, via the connections we have been building in Kenya.

Segments

The market is multi-sided. It starts with the an individual or organization buying the 3D printer. The individual would be a young African that wants to run a business as a 3D printer operator. Organizations involve hospitals, universities and schools. However, the main target of the product is the first segment, the individual 3D printer operator. People we will educate to become 3D printing entrepreneurs. They will produce parts for their local communities.

Costs

The costs are mostly linked to material cost and personnel cost. The material costs are not fixed and can go down as the company grows. Personnel cost can also go down as the company grows, since the production of 3D printers can become more and more efficient. Another part of the cost will be in marketing. Investments in this field need to be made to make people more aware of the opportunity of starting a 3D printing business.

Revenues

Revenue streams will come from multiple sides:
First and foremost revenues will flow through the selling of 3D printers. Other revenues will come in through the selling of plastic materials (filament) for the 3D printers.

References

1. AliExpress. *AliExpress shipping*. 2019 [cited 2019 March 18]; Available from: https://www.aliexpress.com/item/BIQU-BIGTREETECH-TMC2208-V2-0-TMC2130-MKS-Stepper-Motor-StepStick-Mute-Driver-for-MKS-Gen-2/32971481592.html?
2. Jumia. *JUMIA*. 2019 [cited 2019 March 26]; Available from: https://www.jumia.co.ke/.
3. ESMI, *Kenya Quarter 2 Summary Analysis.* 2018.
4. 3D Hubs, *Online Manufacturing Trends.* 2018.
5. WASProject, *DELTA 20 40 TURBO*. 2018.
6. Kats, D., et al. *Paper 3D Printing to Supplement Rural Healthcare Supplies—What Do Healthcare Facilities Want?* in *2018 IEEE Global Humanitarian Technology Conference (GHTC)*. 2018. IEEE.
7. L. Savonen, B., et al., *Development of a Resilient 3-D Printer for Humanitarian Crisis Response*. Vol. 6. 2018. 30.
8. AliExpress. *SIM module SIM800L*. 2019 [cited 2019 March 29]; Available from: https://www.aliexpress.com/item/New-SIM800L-GPRS-GSM-Module-w-PCB-Antenna-SIM-Board-Quad-band-for-MCU-for-Arduino/32622274840.html.
9. Safaricom. *Choosing Your Bundle*. 2019 [cited 2019 March 29]; Available from: https://www.safaricom.co.ke/personal/internet/getting-connected/choosing-your-bundle.
10. Van Bohemen, G.L.A., *Designing a repairability assessment tool.* 2016.
11. Chvalina, T. *6 tips for Original Prusa i3 3D printer maintenance*. 2018 [cited 2019 June 22]; Available from: https://blog.prusaprinters.org/top-6-tips-original-prusa-i3-3d-printer-maintenance/.
12. Nuchitprasitchai, S., M. Roggemann, and J. Pearce, *Three hundred and sixty degree real-time monitoring of 3-D printing using computer analysis of two camera views.* Journal of Manufacturing and Materials Processing, 2017. **1**(1): p. 2.
13. Prusaprinters. *PRUSAPRINTERS FORUM*. 2018 [cited 2019 April 25]; Available from: https://forum.prusaprinters.org/forum/original-prusa-i3-mk3s-mk3-general-discussion-announcements-and-releases/power-consumption-of-mk3/.
14. PowerStream. *How to calculate battery run-time.* [cited 2019 July 11]; Available from: https://www.powerstream.com/battery-capacity-calculations.htm.
15. Accu.nl. *Loodaccu 12V 7Ah (Ultracell UL7-12 VRLA)*. 2019 [cited 2019 June 17]; Available from: https://www.accu.nl/loodaccu-12v-7ah-ultracell-ul7-12-vrla-sla.
16. NKON. *12V loodaccu's*. 2019 [cited 2019 July 12]; Available from: https://www.nkon.nl/rechargeable/lead-acid-batteries/12v-vrla/merk/ultracell.html.
17. HANDYMAN. *Philips Sponsfilter*. 2019 [cited 2019 June 22]; Available from: https://www.handyman.nl/product/philips-sponsfilter-buffalo-powerpro-compact/3400493911/.
18. HANDYMAN. *Scanpart Microfilter*. 2019 [cited 2019 June 22]; Available from: https://www.handyman.nl/product/scanpart-microfilter-voor-stofzuiger-universeel-200x260mm/2684000007/.
19. WTW FILTER STORE. *Filterdoek en Filtermat 1m2 22 mm dik M5*. 2018 [cited 2019 July 13]; Available from: https://www.wtwfilterstore.nl/filterdoek-en-filtermat-1m2-22-mm-dik-m5-afpro-filters.html.
20. DSMT. *IP Rating Chart*. 2018; Available from: http://www.dsmt.com/resources/ip-rating-chart/.
21. RISE. *IP-Classification*. 2017 [cited 2019 July 13]; Available from: https://www.sp.se/en/index/services/ip/Sidor/default.aspx.
22. ANYCUBIC. *Anycubic Ultrabase Series*. 2019 [cited 2019 June 18]; Available from: http://www.anycubic3d.com/products/show/1060.html.