FDM PRINTING IN INDUSTRY 4.0

Extend the capabilities of FDM-printing to Industry 4.0 standard

Acknowledgement

This report only shows a small part of how the project has been. There were many challenges, and I would not be able to reach this milestone without the help of all the people supporting me.

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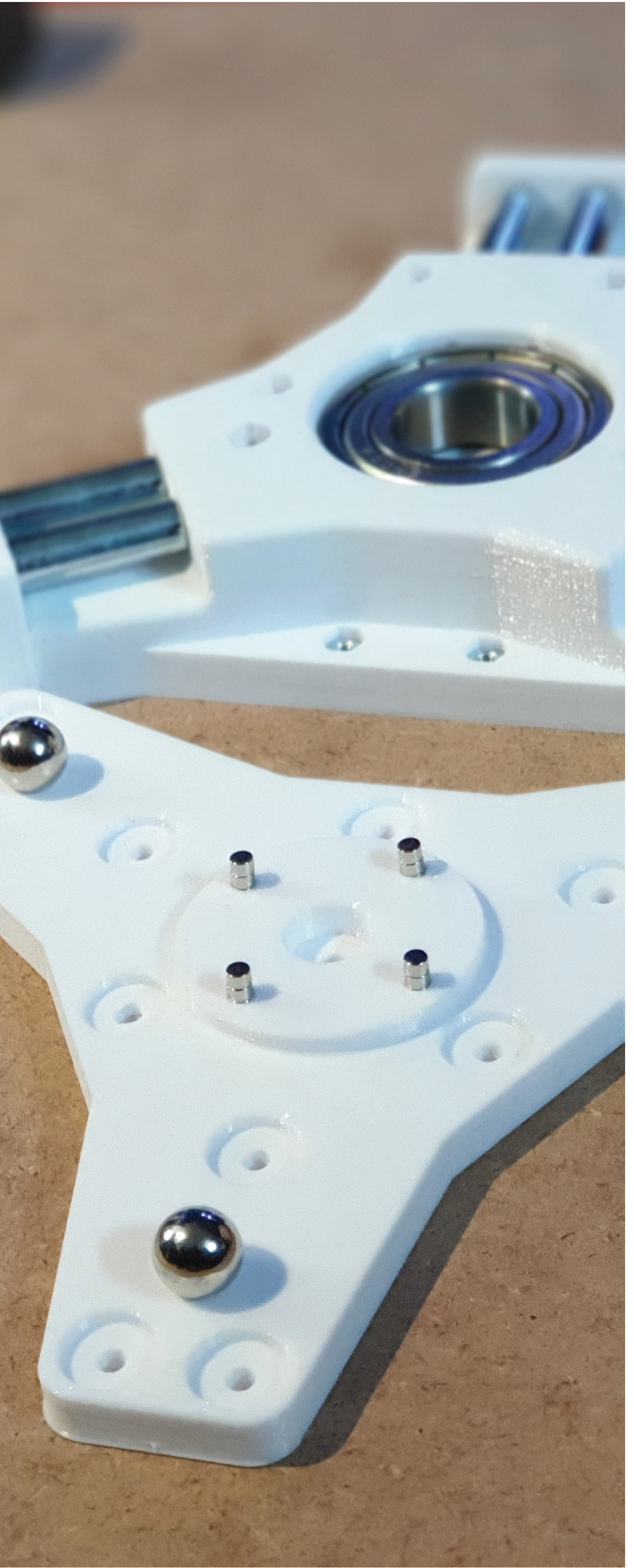


CONTENT

Abstract 3

1 Introduction 4

2 Analysis 8
- 2.1 Company 8
- 2.2 FDM Printing 14
- 2.3 Industry 4.0 28
- 2.4 Trend analysis 38
- 2.5 Workflow 42
- 2.6 Analysis conclusion 44

3 Ideation 46
- 3.1 Design Direction 46
- 3.2 Gaining inspiration (Diverging) 50
- 3.3 First possible solutions 51
- 3.4 Brainstorming 52
- 3.5 Initiating Conceptualization 60

4 Conceptualization 62
- 4.1 Two concepts 62
- 4.2 Concept scenarios 64
- 4.3 Choice of concept 72
- 4.4 Chosen concept 75

5 Embodiment 76
- 5.1 Features 77
- 5.2 Prototyping 84
- 5.3 Redesign, detailed features 98
- 5.4 Evaluation of requirements 108

6 Conclusion 112

References 114

Appendix 124

ABSTRACT

The fourth Industrial Revolution stand for the current trends of automation and data exchange in manufacturing technologies - which comes with a considerable amount of opportunities as most manufacturers attempt to stay ahead of the competition. One of the possibilities is the addition of FDM printing - one of the types of additive manufacturing, also called 3D printing. Currently, FDM printing techniques are not fully industrialized. There is a significant need for human labor. Therefore, there was a need for a solution - on how to integrate FDM printing techniques in a production line by applying the core design principles of industry 4.0. The final design includes and modular systems with high interconnectivity allowing cyber-physical systems to interact through the smart factory.

This project consists of a chapter with an analysis including a company analysis and competitors analysis, the section about FDM printing and industry 4.0 and trend analysis. The ideation phase includes brainstorm sessions, CF session, and decision-making phase. From these ideas, two concepts were developed. In the chapter conceptualization, these two Concepts were tested with three products suitable for 3D printing. Two workflows were made to test these concepts. The most beneficial concept is concluded in physical prototypes - which supports the four pillars of industry 4. The chapter embodiment includes the design with its features including; positioning, continuous printing, automatic refill, temperature control, movement control, quality check and a fitting digital system. Parts of the design were tested with a focus on temperature control, movement control, and positioning. Physical models were built to test positioning and movement control. These steps were evaluated and design drivers from these tests were added to the final design.

1. INTRODUCTION

FDM (Fused Deposit Modelling), Stratasys Ltd.'s trademarked term for FFF (Fused Filament Fabrication), is a manufacturing process where a continuous layer of Thermoplastic material is placed according to a predefined CNC code (Gcode).

FDM, as part of Additive Manufacturing (AM) has been mainly used for rapid prototyping (Materialise. 2017). Opposed to some more traditional rapid prototyping methods as Milling and turning that represent subtractive fabrication processes, AM is a process in which material is added layer by layer to build the desired shape. One of the main advantages AM has over other processes is the fact that there is no restriction caused by tool access, allowing to produce practically any shape desired.

3D Systems were the first company to introduce commercial AM machines in 1987 (Wohlers, T.). Various other companies joined afterwards, with Stratasys being the most notable company in the field of FDM. The expiration of their patent US005121329 (US Patents 1992) marked the start of both the open-source movement RepRap, commercial and DIY variants, all of which use the FDM printing type of 3D manufacturing. Leading to a two-orders-of-magnitude price drop since the introduction of the technology (Rundle, G. 2014). This has allowed drastic developments and inspired companies to look more at the manufacturing capabilities of the technology.

The focus in this project will be on the AM technology FDM. In FDM, parts are manufactured by extruding a thin thread of semi-liquified material (typically thermoplastics) that is accurately moved around in a horizontal plane to shape a physical layered cross-section of the part, the material is immediately solidified after extrusion. (figure 1.1 illustrates this process).

A 3D model is built when the material fuses to the previous layer underneath. The process does allow for overhangs by extruding support material along in the layers. These supports can be made from soluble materials allowing for easier removal as it is simply dissolved in another material (often water).

Most current printers use pre-extruded plastics, that have been stored on spools. In the case of Ultimakers, the extruder moves in the XY plane and the vertical movement is done by moving the print bed in the Z direction.

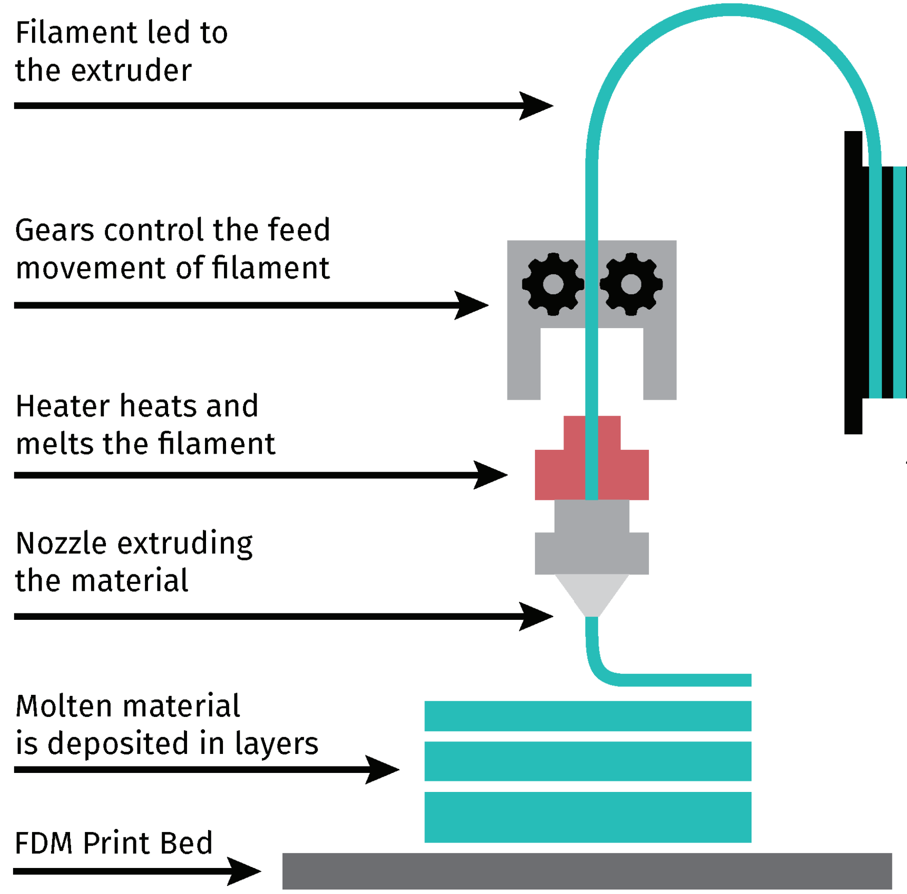


Figure 1.1 FDM Printing basic diagram

Low volume manufacturing

With 3D printing as it is, businesses can already consider short-run part production, where new products can be launched faster and more adaptive. It allows for parts that are not possible to make with traditional methods. (Wright, I. 2018)

3D printing can be more efficient than other production methods for the first several hundred parts (Abplanalp, P. 2018). But to be able to be utilized in the industry is it also usable on a larger scale?

High volume manufacturing

A production line set up for 3D printing can be changed with less adaption than when traditional manufacturing is used, making 3D printing a feasible option. (Kerns, J. 2017)

Improvements in machinery, adjustments to the print speed or even a change of product can be made almost instantly. The capabilities that come with 3D printing and the way in which technology is evolving will enable businesses to adopt newer ways of producing products or parts. (Kerns, J. 2017)

Some the advantages of using 3D printing for manufacturing that were found during the analysis include but are not limited to:

- Reduction in costs
- Reduction of risks
- Failure is cheaper and faster
- Time to market
- Build and grow
- No Limitations in geometries
- Less waste
- Less storage space

Some of the challenges found of using 3D printing for large scale production include but are not limited to

- The cost of the equipment/the financial implications.
- The materials available and usability
- Post processing needs
- Manufacturing costs
- (Lack of) Expertise
- Software development and capabilities
- Recyclability

Industry 4.0

Industry 4.0, also known as: the connected factory, the smart factory and factory of the future (IBM. 2017). Is the fourth industrial revolution. The fourth industrial revolution is the current trend of automation and data exchange in manufacturing technologies. This results in opportunities as most manufacturers attempt to stay ahead of their competition. The complex manufacturing orders are managed in a digital environment by cyber-physical systems. Digital manufacturing is the key to make all of this possible. Figure 1.2 gives an overview of the 4 industrial revolutions and their main feature in short.

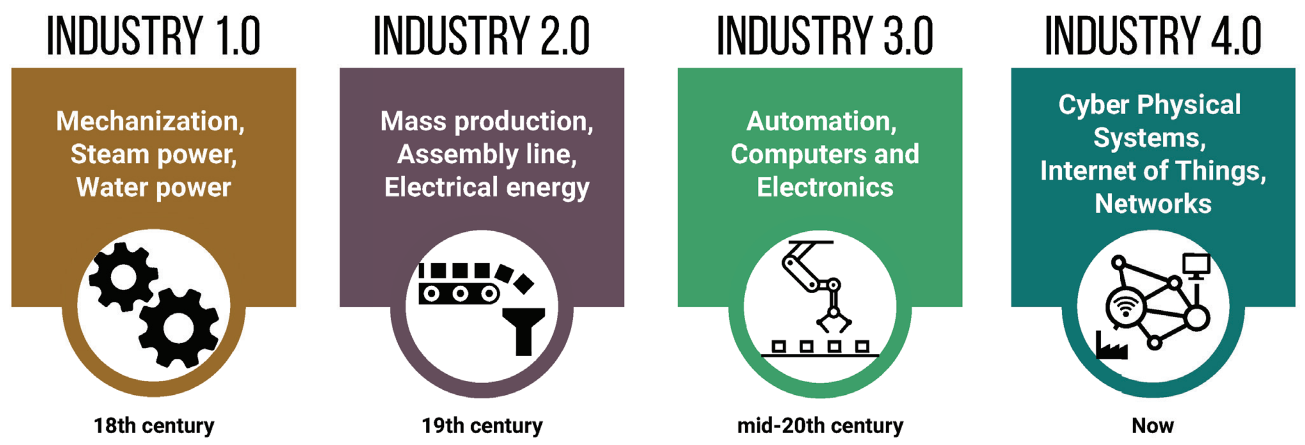


Figure 1.2 Industries 1.0 to 4.0

There is an ever-growing knowledge on digital manufacturing already, however, for most potential users this is far from accessible yet due to technological challenges, making it hard to deal with provided material like computational optimization, computer-aided design, behavioral simulations and related software support (Doubrovski et al., 2011).

For a company like Ultimaker, participation and especially defining within this revolution is key. Designers (among other stakeholders) can play a more individualistic role and deliver a customized tailored product. From a business point of view, keeping up with the industrial revolution 4.0 means Ultimaker can keep up with the current market trends and stay

ahead of their competition. From a societal point of view, there will be more possibilities for centralized production facilities, meaning a lower environmental impact as transport of finalized products is reduced drastically.

The biggest issue are the limitations in accessibility of the new industry, caused by a lack of user friendliness, which applies to intuitiveness, ergonomics, product experience & understandability. There currently is no real smart system, but the technology is there.

This project is set-up and executed as a design process, of which the initial planning is illustrated in figure 1.3. As the process is a design process, it is more circular than linear from week 8 onwards.

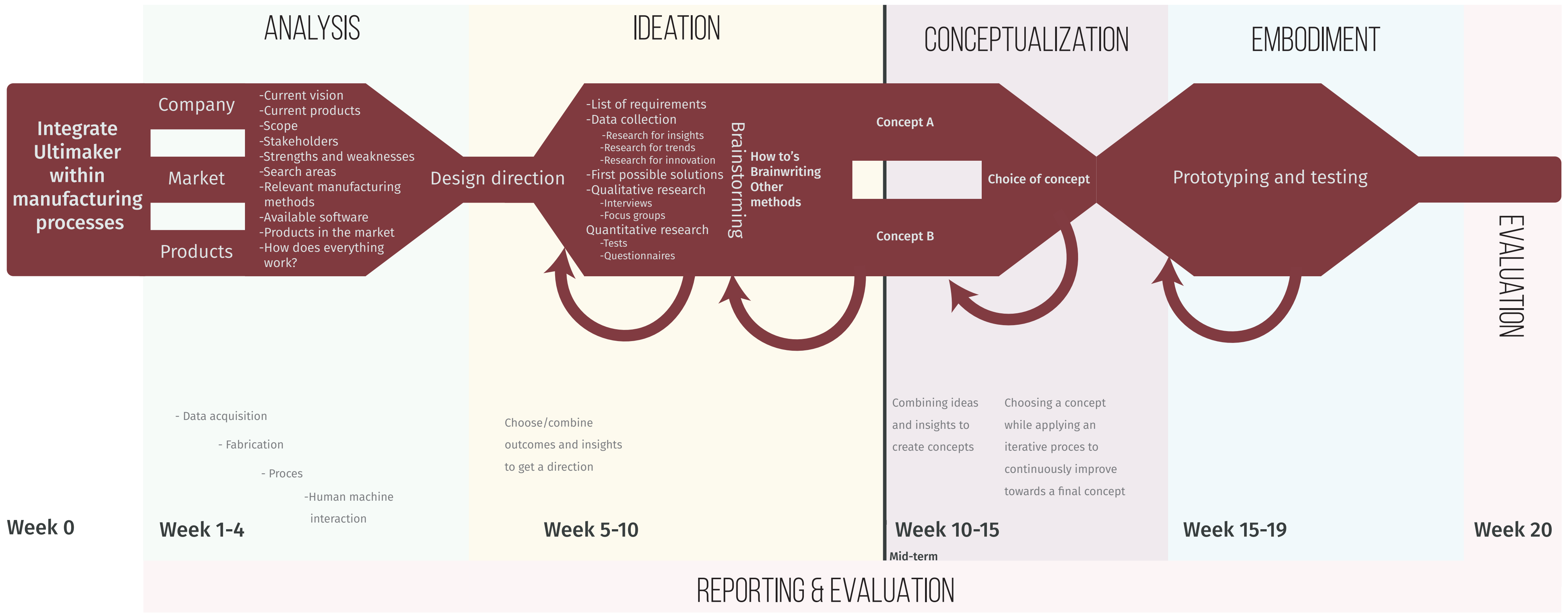


Figure 1.3 Graduation planning

2. ANALYSIS

This chapter will report on the analysis phase. During this phase, research has been done on the company (Ultimaker) (2.1), FDM printing in general (2.2), Industry 4.0 (2.3). Trends have been identified through the DEPEST method (2.4). The workflows of FDM printing and how this will work in industry 4.0 are presented in chapter 2.5. To draw conclusions from the research, various literature studies have been done, interviews were held, methods learned in the Industrial Design bachelor and master were applied and observations were made. The analysis is concluded in chapter 2.6 with design drivers and opportunities along with a list of requirements.

2.1 Company

Ultimaker has been analyzed to get a better understanding of their market position and capabilities.

2.2.1 FDM Materials

Ultimaker was founded in 2011 and in just 7 years, has released multiple printers and grown from 3 people to over 300 employees. Figure 2.1 shows the key events in the development of Ultimaker since the RepRap movement gained popularity in the Netherlands.

Figure 2.1 History of Ultimaker

2.1.2 Products

Ultimaker delivers a complete package for 3D printing. Meaning, they do not only deliver the printers, but also the software, materials and technical support. With the introduction of the S5 (the newest FDM printer in Ultimakers portfolio) they have made an attempt to step away from the makers, towards the industry. It is claimed to be a more reliable printer with higher repeatability. The key features for the S5 can be found in figure 2.2.

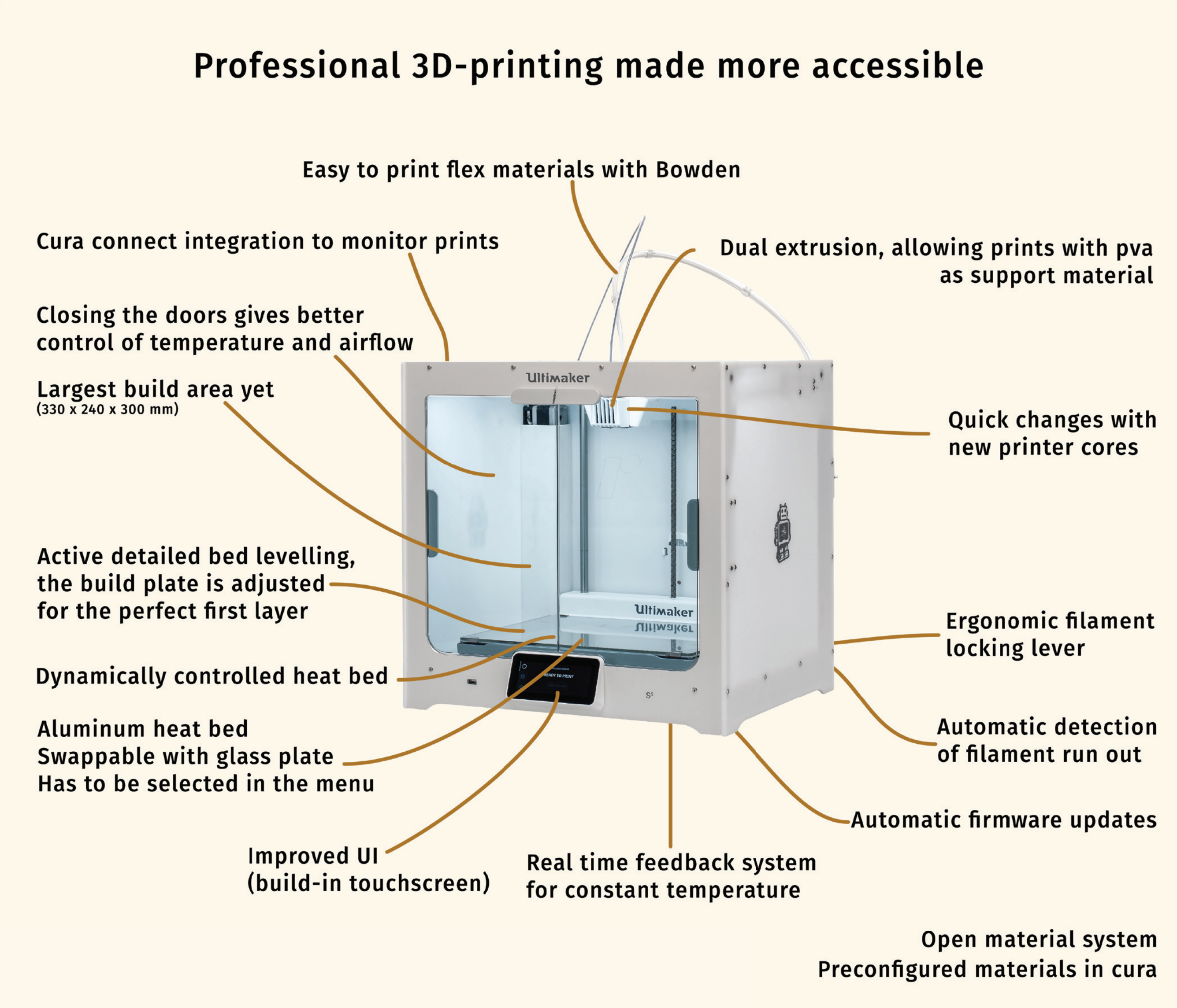


Figure 2.2 Ultimaker S5 features

Ultimaker printers are designed to make high quality prints. The Original family is sold as a DIY kit where the 2, 3 and 5 families are sold as pre-assembled machines. One of the distinctive properties of Ultimaker printers is that vertical movement is accomplished by moving the print platform, not the nozzle. The following printers are currently sold:

- Ultimaker Original+ 2014
- Ultimaker 2 Go 2015
- Ultimaker 2 Extended 2015
- Ultimaker 2+ 2016
- Ultimaker 2 Extended+ 2016
- Ultimaker 3 2016
- Ultimaker 3 Extended 2016
- Ultimaker S5 2018

The software platform Cura can be used to control the printer and with Cura connect multiple printers can be controlled. It comes with a Solidworks Plugin, to export models into Cura with one click. Native AutoDesk Invertor file formats can also be opened in Cura.

Cura is intended to create a seamless integration between a 3D printer, software and materials to achieve perfect prints every time (Ultimaker. 2018). Some features of Cura include:

- Cross-platform, open source software, available for free
- Ability to Print right away using recommended mode while custom mode can be used by advanced users to configure over 300 settings
- Extensively tested profiles created by experts make hardware and material configuration simple and fast
- It supports STL, OBJ, X3D, and 3MF file formats
- Possibility of additional software with plugins
- Can be combined with Cura Connect to manage one or more network-enabled Ultimaker printers from a single interface

An app can be used to control and monitor network-enabled Ultimaker 3D printers and provides live notifications on the progress of the print.

2.1.3 Founding values

Ultimaker has had the mission to accelerate the world's transition to local digital manufacturing from when they were founded. They have some values mentioned as founding values, illustrated in figure 2.3.

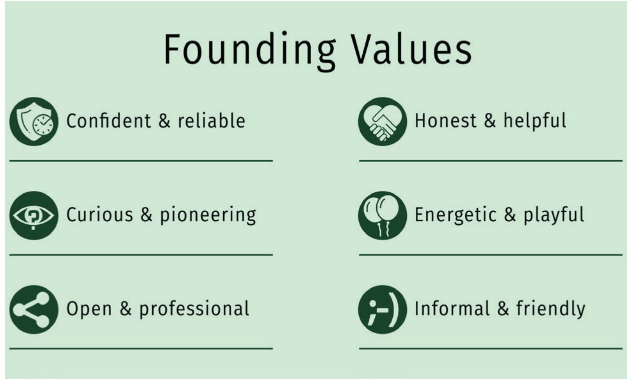


Figure 2.3 Founding values

2.1.4 Competitors

To identify the competitors and market in which Ultimaker acts an onion diagram was made which can be found in figure 2.4, this diagram and the diagram discussed in 2.1.5 (Stakeholders) were presented and agreed upon during the first meeting with Ultimaker. In an onion diagram, the product form contains competitors that have products of the same product type. Category are products with similar features that provide the same basic function. Generic stands for products that fulfill the same basic needs and budget are the products that compete for the same discretionary budget allocation, this has not been filled as it can encompass any form of production and prototyping.

When moving towards the industrial side of the spectrum, which is the goal in this project, the product form will also move more toward the professional side of the Product category, meaning the direct competitors will be companies like Stratasys, Markforged, Zortrax, Leapfrog and Raise3D.

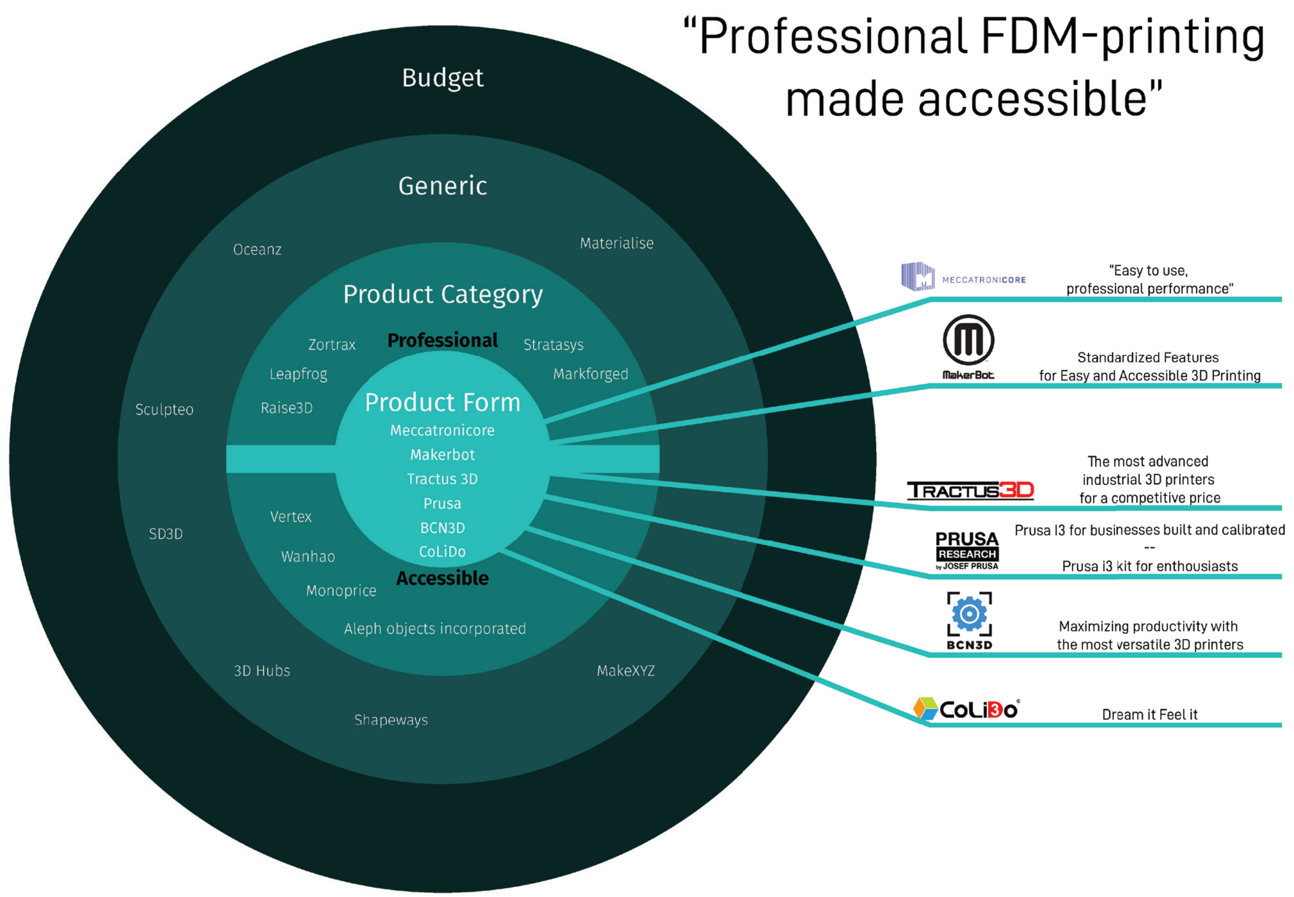


Figure 2.4 Competitors onion diagram

2.1.5 Stakeholders

A stakeholder analysis was done for when Ultimaker enters the Industry and is illustrated in the onion diagram in figure 2.5, to identify what the stakeholders are, how close they will be and whether the changes proposed in this thesis will have a positive, neutral or negative effect. In the diagram, the inner circle means the proposed change in product form, so Ultimaker creating an Industry 4.0 solution. The second layer is the business system and show the stakeholders that directly interact with the product. The third layer contains what hosts or controls the product, which Alexander, I. (2003) described as “functional beneficiaries of the system”. The fourth layer contains the wider environment in which the company operates. Furthermore, in appendix A, a list of the fields utilizing FDM printers (according to Ultimaker) can be found and how they use it.

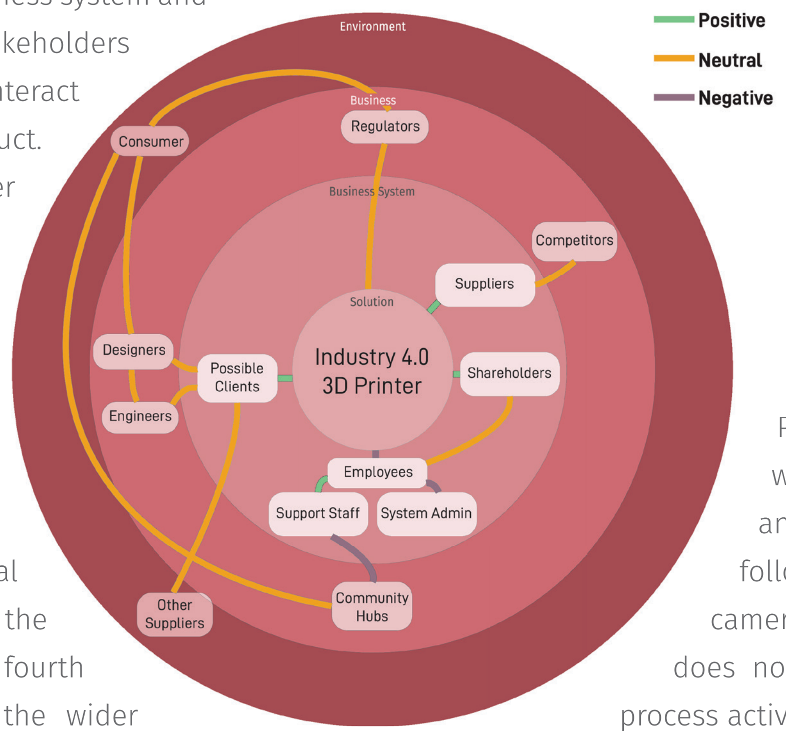


Figure 2.5 Stakeholder onion diagram

2.1.6 The Ultimaker print farm

In an attempt to increase production, Ultimaker, like other companies, built a print farm. With the current workflow, the Ultimaker print farm (28 printers) could be supervised by one full-time employee. An important comment here is that all products were exactly the same, making the process significantly easier compared to having different prints with different settings. Prints can be sent wirelessly to the printers and the process can be followed remotely via a live camera. The camera however, does not monitor the printing process actively.

The 28 printers in Ultimakers’ own print farm allowed them to produce 700 spool holders in less than 4 weeks. With everything set up, they achieved a print success rate of around 86% and a calculated average uptime of 92% (Lozova, L. 2016).

Those look like impressive numbers but when calculating with it the following shows. Printing the spool holder took about 18 Hours (Ultimaker, 2016). This means that that 2051 hours were lost due to failed prints and the printers were Idle for 1172 hours. That is more than 4.5 hours lost per print.

Requirements Chapter 2.1 Company:

- Must offer a complete package
- Must be able to access the Cura material database
- Fits in the professional product category of the competitor diagram
- Decreases idle time of the printer

2.2 FDM Printing

The technology of FDM printing has been research to find developments and analyze how it works. This chapter reports on that research by looking at the materials (2.2.1), the printing surfaces (2.2.2), a comparison was made between industrial (targeted direction) and desktop FDM printing (current market of Ultimaker) (2.2.3), sensors in the printers (2.2.4), a use case of FDM in production (2.2.5) and a comparison between FDM printing and traditional production method, mainly injection molding (2.2.6). FDM is the patented (by Stratasys) name for the technology and stands for Fused Deposition Modeling which is the exact same thing as FFF, Fused Filament Fabrication. For consistency the term FDM will be used as that is the most found name used in the industry.

2.2.1 FDM Materials

One of the key features of FDM printing is the wide range of materials available. Which will be discussed in this chapter.

The amount of available materials and types of filament are rapidly growing, especially with the increasing amount of chemical companies joining the FDM market (3D Print Magazine. 2018). There are various exotic filaments like woodfill or steelfill, those consist of a combination of fibers and one of the existing FDM materials (for example a combination of steel fibers and PLA). Figure 2.6 shows the thermoplastic materials available in FDM, the material Pyramid by 3d hubs (3dhubs, 2017) was used as a starting point. In this pyramid the general rule can be applied where the higher the material, the higher the performance and costs are, the higher the temperature needed for printing. The printing properties of these materials are described in appendix B. Materials. The high-performance materials require special printing conditions, machines capable of printing those materials are specifically designed to meet these conditions drastically increasing the price of these machines (AMFG, 2018). It is a different market compared to the engineering and commodity materials as high-performance materials are seen as alternative to metal alloys. Therefore, the intended concept will not have to be capable of printing with these materials.

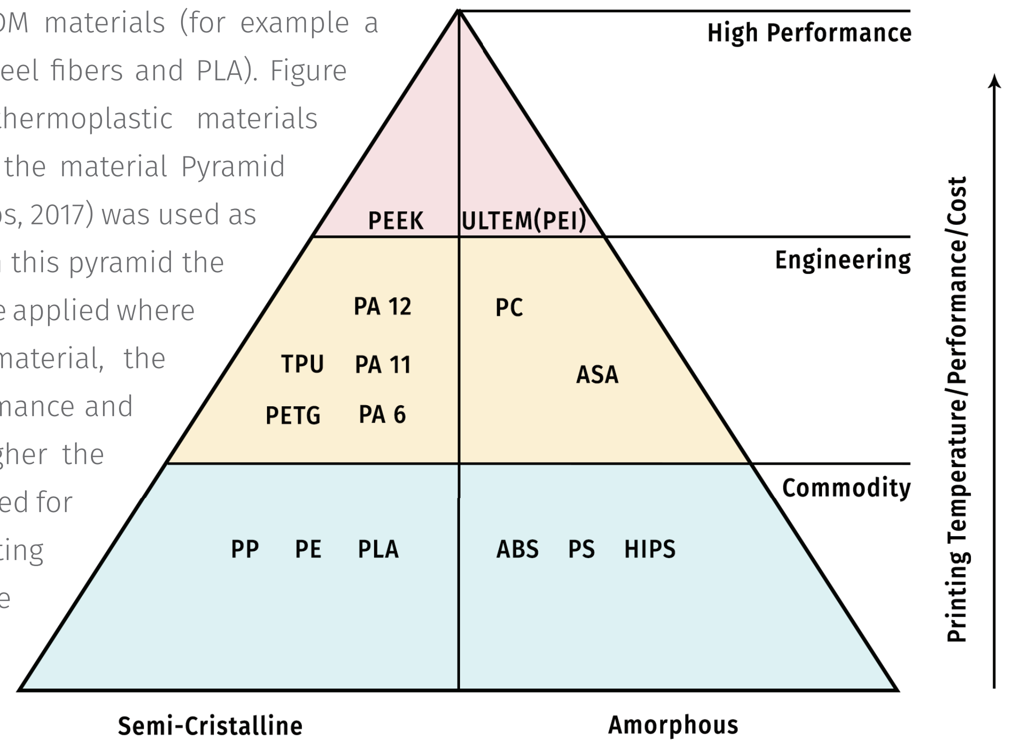


Figure 2.6 Thermoplastic materials pyramid

2.2.2 Printing surfaces

Desktop FDM printers have seen a big development since their introduction in 2011. During this development various printing surfaces have been introduced to improve the process (Robo3D. 2018). When printing the surface is required to adhere to the print, but not too much as the print has to be removable after it is finished. Appendix C lists the most common surfaces with their advantages and disadvantages and discusses the potential of their application in the concept. It differs per printing material which surface is best suited (Anderson, T. 2016), so this has been discussed in appendix C as well.

Requirements Chapter 2.2.1 FDM Materials:

- Must be able to work with a wide range of materials
- Must be able to support new and improved materials
- Must be able to combine printing material with support material
- Must be able to print engineering grade materials
- Materials must be stored in optimal environment (dry)

Requirements Chapter 2.2.2 Printing surfaces:

- Must have a strong adhesion during printing
- Part can be released after printing is finished
- Printing surface matches the material that will be used for printing

2.2.3 Industrial FDM (Direction) and Desktop FDM (Current)

Most of the low-cost desktop 3D printers are based on FDM (while SLA resin printers are also gaining in popularity) (3DHubs. 2018). Ultimaker falls in the category of desktop printer brands. It is possible to compare the desktop and the high-end industrial printers as both are based on the same technology of material extrusion and building products layer-by-layer. Their capabilities are different though. An overview of these differences is given in Table 2.1. These differences will be discussed in this chapter, along with a range of FDM printers by Stratasys.

Property	Industrial FDM (as described by 3D hubs)	Ultimaker S5 (as researched)	Desktop FDM (as described by 3D hubs)
Standard accuracy	±0.15% (lower limit: ±0.2 mm)	0.5% (lower limit: ±0.5 mm)	±1% (lower limit: ±1.0mm)
Typical layer thickness	0.18 – 0.5 mm	0.1 – 0.25 mm	0.10 – 0.25 mm
Minimum wall thickness	1 mm	0.7 mm	0.8-1 mm
Maximum build envelope	Small to Large (e.g. 900 x 600 x 900 mm)	330 x 240 x 300 (in between)	Medium (e.g. 200 x 200 x 200 mm)
Common materials	ABS, PC, ULTEM	PLA, Nylon, ABS, CPE, CPE+, PC, TPU 95A, PP, PVA	PLA, ABS, PETG
Support material	Water-soluble	Water-soluble	Typically, the same as part
Production capabilities	Low/medium	Low	Low
Machine cost	€6.000 - €500.000 (Statasys printer range)	€5.500	€500 - €5.000

Table 2.1 Overview industrial vs Desktop FDM printers

Within the industrial segment of FDM printers there is a wide range of different printers. To illustrate that range the FDM printers of Stratasys have been put in a graph (figure 2.7). This range was chosen as Stratasys is the market leader in industrial FDM printing and covers the spectrum of price and performance (Kay, A. 2018). Table 2.2 adds the numbers to the printers show in figure 2.7 to show the differences between industrial printers. The following chapters will discuss the results presented in both tables 2.1 and 2.2.

Figure 2.7 Stratasys industrial FDM printer range

	Mojo	Uprint	F120	F170	F270	F370	F380MC	F450MC	F900
Material options (according to Stratasys brochures)	1, Commodity (ABS)	1, Commodity (ABS)	2, Commodity & Engineering (ABS-M30, ASA)	4, Commodity & Engineering (ABS-M30, ASA, PLA, FDM TPU 92A)	4, Commodity & Engineering (ABS-M30, ASA, PLA, FDM TPU 92A)	5, Commodity & Engineering (ABS-M30, ASA, PC-ABS, PLA, FDM TPU 92A)	8, Commodity & Engineering (ABS-M30, ABS-M30i, ABS-ESD7, ASA, PC-ISO, PC, PC-ABS, FDM Nylon 12)	10, Commodity, Engineering & High performance (ABS-M30, ABS-ESD7, ASA, PC-ISO, PC-ABS, FDM Nylon 12, FDM Nylon 12CF, ST-130, ULTEM 9085 resin, ULTEM 1010 resin)	10, Commodity, Engineering & High performance (ABS-M30, ABS-ESD7, ASA, PC ISO, PC-ABS, PPSF, FDM Nylon 12, FDM Nylon 12CF, FDM Nylon 6, ST-130, ULTEM 9085 resin, ULTEM 1010 resin)
Second nozzle	Support material								
Build envelope (mm)	127x127x127	203X203x152	254x254x254	254x254x254	305x254x305	355x254x355	355x305x305	406x355x406	914x610x914
Price (advised)	~ €5.000	~€14.000	~€14.000	~€18.000	~€22.000	~€31.000	~€150.000	~€190.000	~€220.000
Part accuracy (according to Stratasys brochures)	±0.2 mm or ±.002 mm/mm (Which one is greater)	±0.2 mm or ±.002 mm/mm (Which one is greater)		±0.2 mm or ±.002 mm/mm (Which one is greater)	±0.2 mm or ±.002 mm/mm (Which one is greater)	±0.2 mm or ±.002 mm/mm (Which one is greater)	±0.127 mm or ±.0015 mm/mm (Which one is greater)	±0.127 mm or ±.0015 mm/mm (Which one is greater)	±0.09 mm or ±.0015 mm/mm (Which one is greater)

Table 2.2 Overview Stratasys industrial FDM printers

2.2.3.1 Accuracy

Geometric tolerances and accuracy of prints are influenced by a range of variables but rely mostly on printer calibration, model complexity and slicing optimization.

According to Bournias Varotsis, A. (2016) The accuracy of industrial FDM 3D printers is higher than that of desktop FDM printers. This is caused by closer control of the processing parameters. Industrial machines run calibration algorithms before each print which now is happening to a certain extend on desktop printers as well. This includes a heated chamber which decreases the effects of cooling of the printed part due to draft/ambient temperatures. This causes warping, as illustrated in figure 2.8. Some industrial printers are able to operate at higher printing temperatures as well. Most of the industrial machines support dual extrusion. This way, water-soluble support materials can be used, which is removed during post processing, resulting in smoother surfaces and allowing for more complex parts. It was found that extruding support material is the main use and purpose of the second extruder in industrial machines. Meaning the second extruder is not used to combine 2 different materials which is one of the selling points for multi-material units on desktop printers.

Most of these features are possible on Ultimakers since the Ultimaker 3. However, the tolerances are lower and a heated chamber is missing, the S5 does have doors added to the front but the printing area is not fully enclosed as the top is open. The doors do stop most of the draft but the print environment can change during a print. This causes irregularities in prints and thus removes precise reproduction as there are unknows added to the equation that influence the end result. If Ultimakers are to be used in the industry these features have to be made up to the industrial standard.

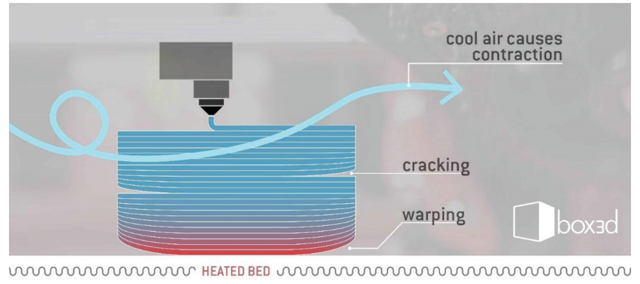


Figure 2.8 Effects of ambient temperatures (source, Box3D)

Other desktop printers are catching up as well. A well calibrated basic desktop FDM machine can produce parts with tolerances of ± 0.5 mm and with the same minimum feature size as industrial printers (Cahoon, S. 2018). This accuracy is good enough for most applications according to Cahoon.

2.2.3.2 Available materials

The most common and easy to use material used on desktop printers is PLA (the black variant) (Booth, N. 2018). If more strength, higher ductility and thermal stability is needed ABS and PETG are two of the most common materials. ABS warps easily, making it harder to print especially in machines that do not have a heated chamber. PETG has similar material characteristics as ABS while it is easy and more reliable to print with. These three materials are suitable for prototyping for form fit and function and even low-volume production of models and functional parts. More on these materials can be found in chapter 2.2.1 (FDM Materials).

Industrial printers mainly print with engineering grade plastics (figure 2.6). These materials can contain certain additives that alter their mechanical properties and make them more useful for certain industrial needs (Tractus. 2018). Materials printed with industrial printers can have comparable material properties to their injection molded counterparts and can be suitable as functional end parts. Their temperature resistant properties also make them suitable as molds for low run injection molding (Fuges, M. 2018).

2.2.3.3 Build volume

As can be seen in table 2.2 there is not a specific built volume which is aimed for, it is rather dependent of the application. It can be seen that, as the performance and costs increase, the build volume increases as well. A bigger build volume results in bigger parts or more parts printed in a single batch. Bigger prints do result in a higher printing time, as the amount of material extruded stays the same (unless the nozzle size is increased as well, resulting in a lower accuracy).

2.2.3.4 Production capabilities

Production capabilities for desktop machines are low, some industrial printers have a medium capability due to a bigger build volume or some form of automation (Stratasys. 2017), figure 2.9 illustrates 3 Stratasys concepts to increase the production capability of FDM printers by combining multiple printers with some form of automation (1), a printing system with an endless build (printed part moves out of the printer) with a robotic arm used to control the process (2).

Figure 2.9 (1) Stratasys Continuous build

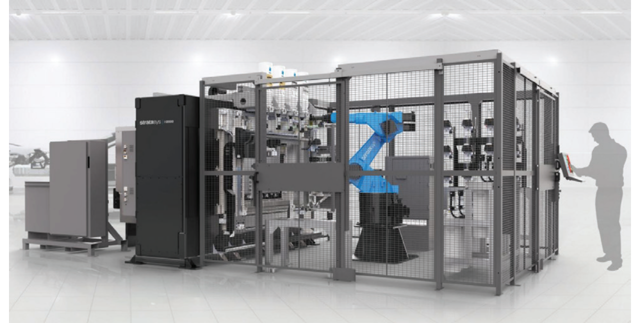


Figure 2.9 (2) Stratasys Infinity Build

2.2.3.5 Costs

A major difference between desktop and industrial printing is the associated cost. The rise in popularity of desktop printers has reduced the cost of desktop FDM printers and their consumables (like filament). This is also lowering prices for the industry, as filament production is increasing and the production methods become more precise (Tractus3d, 2017).

Production capabilities of industrial printers are typically higher than desktop printers, so an industrial printer can complete a large order faster than a single desktop printer. This is the case when a single industrial printer is put up against a single desktop printer. Increasing the amount of desktop printers against this single industrial printer (as multiple desktop printers can be purchased for the price of a single industrial printer) results in a higher throughput for the desktop printers.

Industrial printers are designed for repeatability and reliability. They can often produce the same part continuously while desktop printers require a higher level of user maintenance and regular manual calibration to keep performing, but still at a lower tolerance level than industrial printers.

"An industrial company would rather have 10 bad prints that are exactly the same than 10 prints with differences of which 4 are really good."

-Braam, D. (Cura & Ultimaker)

2.2.3.6 FDM Limitations

FDM can produce high quality parts with durable materials that retain their mechanical properties over time making it one of the more popular techniques. (Tofail, S. 2018) The dimensional accuracy of both desktop and industrial FDM 3D printers is suitable for most prototyping, modelling or low-volume manufacturing requirements.

The minimum feature size of both grade of FDM machines is limited by the diameter of the nozzle and the layer thickness. Material extrusion makes it impossible to produce vertical features with geometry smaller than the layer height. This relatively high layer thickness also can cause the unwanted "stair-step" effect. Features in the XY plane that are smaller than the nozzle diameter cannot be produced while walls must be at least as wide as the nozzle diameter. If smooth surfaces and very fine features are needed post-processing can be necessary (like sandblasting and machining) or other production methods are more suitable.

Requirements Chapter 2.2.3 Industrial FDM (Direction) and Desktop FDM (Current) :

- Must have a standard accuracy of ±0.15% (lower limit: ±0.2 mm)
- Must be capable of printing with a layer thickness in a range of 0.1 – 0.25 mm
- Must have a heated chamber for controlled printing parameters
- Must be capable of printing with a minimum wall thickness 0.7 mm
- Must have a build envelope of 215x215x200/ printing unit
- Must be capable of dual extrusion, second extruder for water-soluble support
- Maximum cost of €10.000 per printing unit
- Ability to print engineering grade materials
- Prints must leave the printer without human interference
- Must be able to combine multiple printing units
- Must decrease user maintenance
- Must decrease human necessity
- Must increase throughput of parts

2.2.4 Sensors

A research on possibly useful sensors has been done, analyzing all available sensors and their functions to see whether they would prove to be of added value for the FDM process. A full overview of this research can be found in appendix D, the results will later be used in the ideation and conceptualization phase.

2.2.4.1 Sensors used

In the interview with Jaime van Tessel – Cura software team (Appendix E. Input from experts) the sensors present in Ultimakers and their use were discussed. During printing the only sensors used are a flow sensor (introduced in the s5 as it was absolutely necessary) and a thermistor in both the heat bed and the extruders as this is essential for the printing process (Tessel, J. 2019). There are no further sensors included as this would make the process more complex and increase the price of the machines, which is an important factor in the current market Ultimaker is in, with hobbyists and consumers (Ruizenaar, R. 2019). A proximity sensor in the extruder is used for active leveling at the start of each print, to create a reliable first layer. In this process, a detailed heightmap of the printing surface is made. The data collected is then used in the first centimeter (Marx, S. 2019) to make up for any inaccuracies in the printing surface. This is done by adjusting the build plate height while printing (Ultimaker. 2018).

2.2.4.1 First layer

The calibration of the first layer can be done with different kinds of sensors. The most common and relevant sensors have been analyzed and rely on the type of surface they need to scan. These sensors have been listed and are discussed in appendix F.

Requirements Chapter 2.2.4 Sensors:

- Must have the option to monitor the process autonomously
- Must detect errors
- Must have an automatic first layer calibration

2.2.5 FDM in production and the costs

This chapter will analyze what influences costs of 3D printing production and how these costs can be decreased to improve their industrial adoption. According to David Feeney, improving uptime and reliability by reducing machine failures is the most important aspect to decrease the cost of 3D print production. This finding has been reinforced by the data that was gathered in a research on ten unmodified FDM printers (including Ultimakers) in a timespan of six months, with a combined total of over 30,000 printing hours done by SD3D (SD3D Printing. 2018), they made a diagram of their technician's time allocation, found in figure 2.10.

Automation is key in reducing the time allocation, as nearly all time is spent on tasks that can be automated, loading filament, software preparation, part removal, cleanup and printer preparation are all part of this. These findings have been partially confirmed during the interview with Schönfeld, R. (An extract of this interview can be found in appendix E. Input from experts) who maintained a print farm of 20 Ultimaker 2+ printers at the faculty of Industrial engineering in Delft. He described that the time allocation for the proposed tasks is correct but some tasks are missing. These tasks are monitoring (especially the first entire layer) of prints, which is the most time-consuming task of all and calibration of the printers, which is the least time-consuming since the manual part of this process is only done once per month by him.

SD3D is developing modular subsystems which manufacturers can use within their existing products' tool chain as a plug-and-play system. It has either removed or reduced order preparation, software preparation, part removal and fixing failures from the technician workflow.

Figure 2.11 demonstrates SD3D's findings on their subsystems' savings. It shows exactly the costs that are added when a technician operates a print farm.

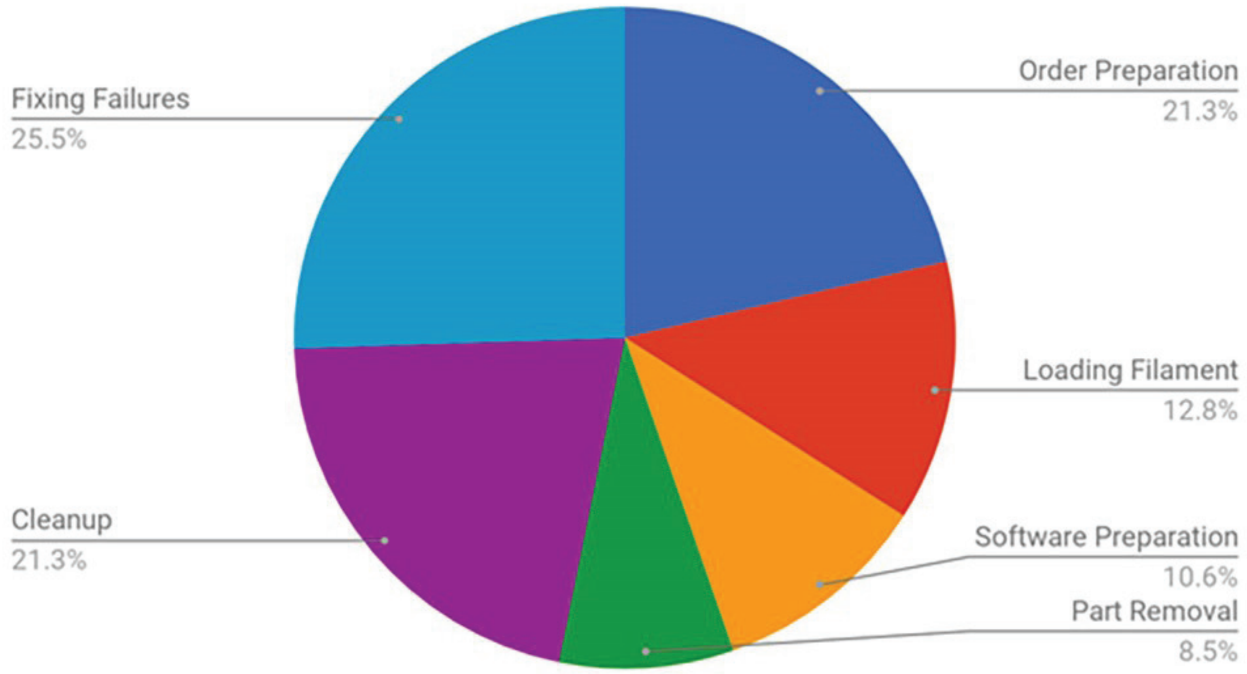


Figure 2.10 Technician time allocation (as found by SD3D)

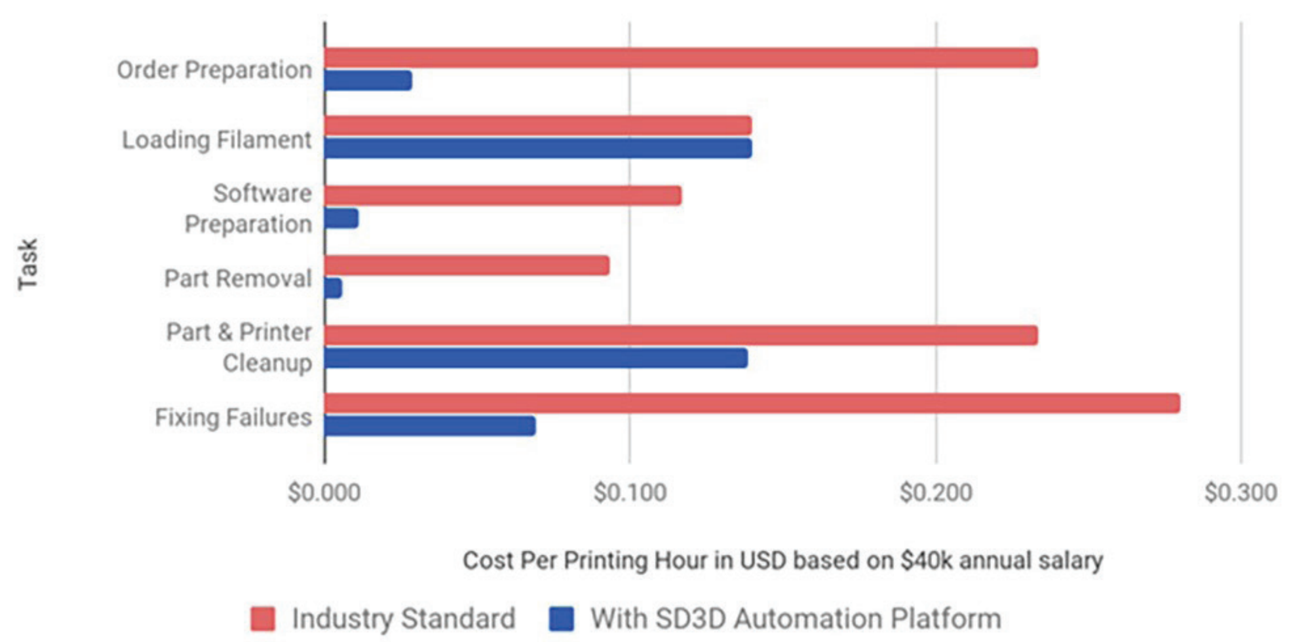


Figure 2.11 Cost of technician time by task (as calculated by SD3D)

Since it is an American study the amounts are in dollars, the labor cost per printing hour ranges between $0.39 per printing hour with their automation system and $1.10 per hour without it for these selected printers. The calculations can be found in appendix G. With SD3D's automation platform it was found that the total costs of space, energy, material and labor are $43.59 per kg without it, meaning the current situation, the price will then be $74.83 per kg. With more expensive materials and printers this can eventually exceed $300/kg, in a good printing environment these materials can be replaced by generic alternatives while maintaining print quality and reliability.

It must be noted that these numbers come from a commercial study and the exact ways of operation are not shown, making it somewhat doubtful if their solution actually results in these amounts of saving. However, the numbers do show the impact automation will have on FDM printing by decreasing the human operation time.

Requirements Chapter 2.2.5 FDM in production and the costs:

- Must increase the printer uptime
- Must decrease human intervention for
  - Fixing failures
  - Order preparation
  - Loading filament
  - Software preparation
  - Part removal
  - Cleanup
  - Monitoring
  - Calibration
- Must increase automation in the workflow (Chapter 2.5)

2.2.6 FDM printing against conventional methods

This chapter discusses how FDM printing (in print farms) holds against conventional production methods to identify strengths and weaknesses of FDM printing. The chapter will mainly look at injection molding as this has the closest result to FDM printing. Various researches have already been done in the differences and the most relevant results will be presented and discussed here, by looking at cost per part, speed, batch volume, strength, complexity, accuracy and flexibility.

2.2.6.1 Cost per part

The costs per part found differ drastically per research done. With the price per part inflection point being dependent of factors as, among others, volume, complexity, accuracy and material (Slant3d, 2017). The graph does however always look like figure 2.12 when comparing the processes.

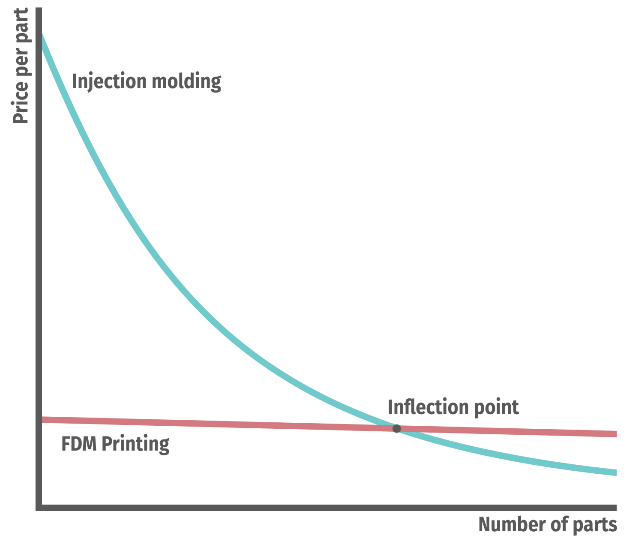
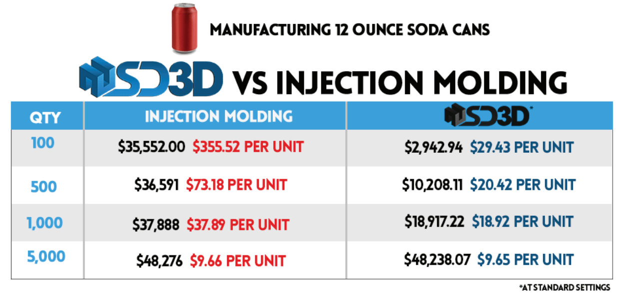


Figure 2.12 Cost per part, FDM vs injection molding

FDM-printing is faster with the first parts, but is caught up when a large quantity of the exact same product is needed (thousands). This difference is caused by the difference in investment costs for the setup and tooling. Leaving purchase costs for printers and injection machines out of the equation. The number of parts where injection molding becomes cheaper is changing continuously as innovations and new technologies are introduced (Kohm, A. 2016).

In 2015 SD3D claimed their inflection point against injection molding was around 5.000 parts when having a 350ml can as an exemplary product (figure 2.13). SD3D is a company that automates the processes of additive manufacturing and provides 3D printing services.


MANUFACTURING 12 OUNCE SODA CANS

SD3D VS INJECTION MOLDING

QTY	INJECTION MOLDING	SD3D*
100	$35,552.00 $355.52 PER UNIT	$2,942.94 $29.43 PER UNIT
500	$36,591 $73.18 PER UNIT	$10,208.11 $20.42 PER UNIT
1,000	$37,888 $37.89 PER UNIT	$18,917.22 $18.92 PER UNIT
5,000	$48,276 $9.66 PER UNIT	$48,238.07 $9.65 PER UNIT

*AT STANDARD SETTINGS

Figure 2.13 FDM vs injection molding (according to SD3D)

For this job a tooling cost of $34.983 was calculated, meaning any change during the process means an extra $34.983 has to be invested. This will further be discussed in 2.2.6.7 Flexibility. With the price per unit decreasing faster for injection molding (figure 2.12) the inflection point in this case can be seen at 5.000 parts.

2.2.6.2 Speed

There is a big difference in speed, in this case the time between the idea of a product and actually having the finished part. FDM printing started as a rapid prototyping tool for this reason as, in most cases the part can be acquired within 24 hours, where CNC machining can be done within a week, for the first part to be completed with inject molding a time of 6 to 8 weeks can be estimated due to the production of necessary tools (Tempelman, E. 2014).

2.2.6.3 Batch volume

Volume is about the speed of production as well, the duration to produce a single component. For FDM printing a single part, with a single Ultimaker printer can take multiple hours to days (for very big, low layer height prints), which works for low volume parts that have a high price (Cura, 2019). If hundreds of parts are needed in one day however, this will require a multitude of printers. Once a mold is made for injection molding this can be achieved as the production times are significantly lower, often less than a minute per part (Tempelman, E. 2014).

2.2.6.4 Strength

There used to be a clear difference in the strength category. As a product is built by adding layer after layer, the bond between these layers used to be weaker than a solid piece of the material. Leading to parts with lower strengths for FDM printing (Proto21, 2016). New methods of producing (Markforged, 2018), post processing (Kuznetsov, V.E. 2018), annealing (Jorgenson, L. 2017), adding fibers to make composites (Markforged, 2018) and improved materials (Ultimaker, 2018) have decreased this effect.

2.2.6.5 Complexity

One of the key advantages of FDM printing is the freedom in complexity (Linneman, A. 2017). Injection molding is restricted by the fact that the mold has to release, causing certain complex products to have a high initial molding costs or to be impossible to be made at all. There is no such limitation for FDM printing. Practically any shape is possible with the technique, figure 2.14 illustrates an object that is only possible to make with additive manufacturing, in this case a multi-material system is required as support material is dissolved after the print. The choice for production method is dependent of the product that is to be made and the expected result. In case of tolerances, injection molding performs better (ProtoCAM, 2018).

Figure 2.14 Ultimakers 3D printed gyro

2.2.6.6 Accuracy

FDM printed parts are generally not finished after printing, the production method requires some form of post processing or machining afterwards to get a desired finish or receive the desired tolerances. However, progress is being made in this category and within a few years this might not be required anymore (Ultimaker. 2018). Injection molding on the other hand is already capable of delivering high quality and end use products (Tempelman, E. 2014).

2.2.6.7 Flexibility

Flexibility is another key advantage of FDM printing (Kohm, A. 2016). One printer can create different parts without the need for change of the setup or tools. Where injection molding immediately requires a new mold for a changed product.

Requirements Chapter 2.2.6 FDM printing against conventional methods

- Must combine the power of multiple extruders, to increase production
- Must not need new tools to change printed product
- Must maintain the freedom of complexity
- Must maintain a flexible system, where upgrades and updates can be added
- Must allow for post processing

2.3 Industry 4.0

In order to gain an understanding of what Industry 4.0 is and means an initial research on the topic was done, figures 2.15 and 2.16 summarize the findings in short that will be covered in this chapter. Other terms for industry 4.0 that were found, depending on which part of the world uses it, include: the connected factory, the smart factory and factory of the future (IBM. 2017). Key for the research were the four pillars (chapter 2.3.1) and four core principles (chapter 2.3.3) that have been identified after a literary study which should all be implemented for production in industry 4.0. The role of additive manufacturing in Industry 4.0 is researched in chapter 2.3.4.

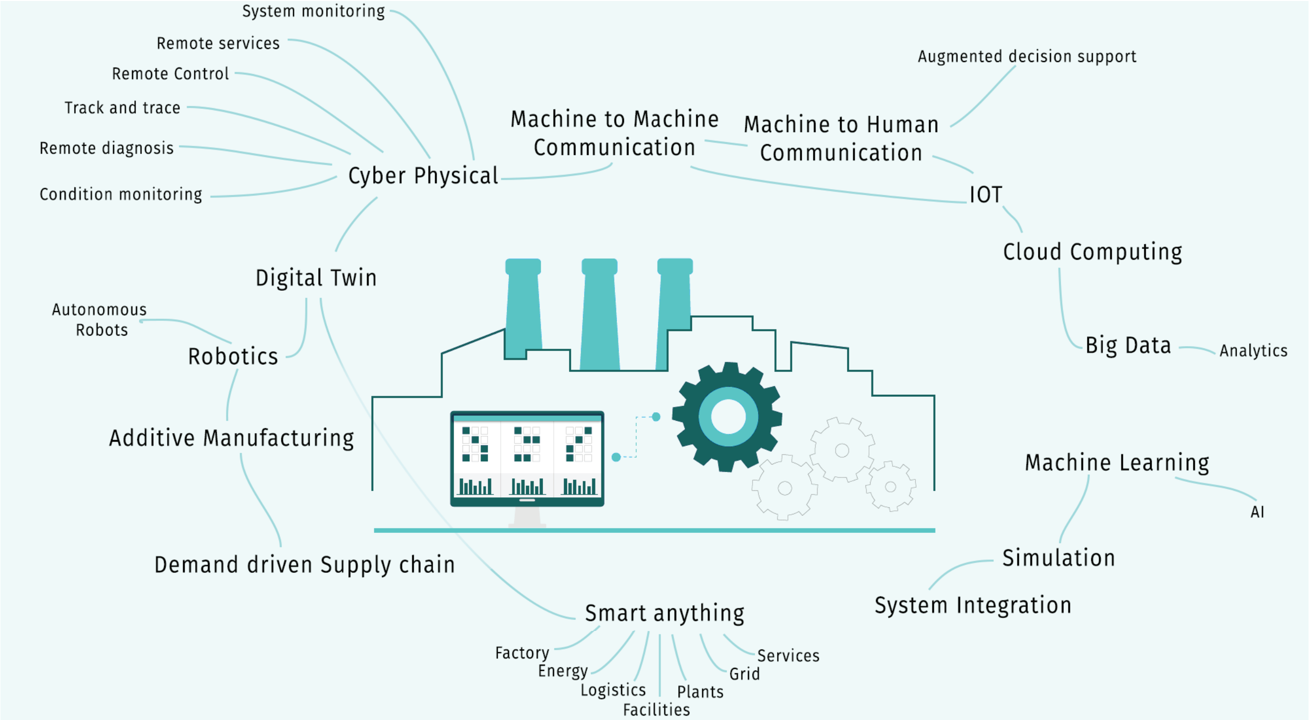


Figure 2.15 The industrial sector of industry 4.0

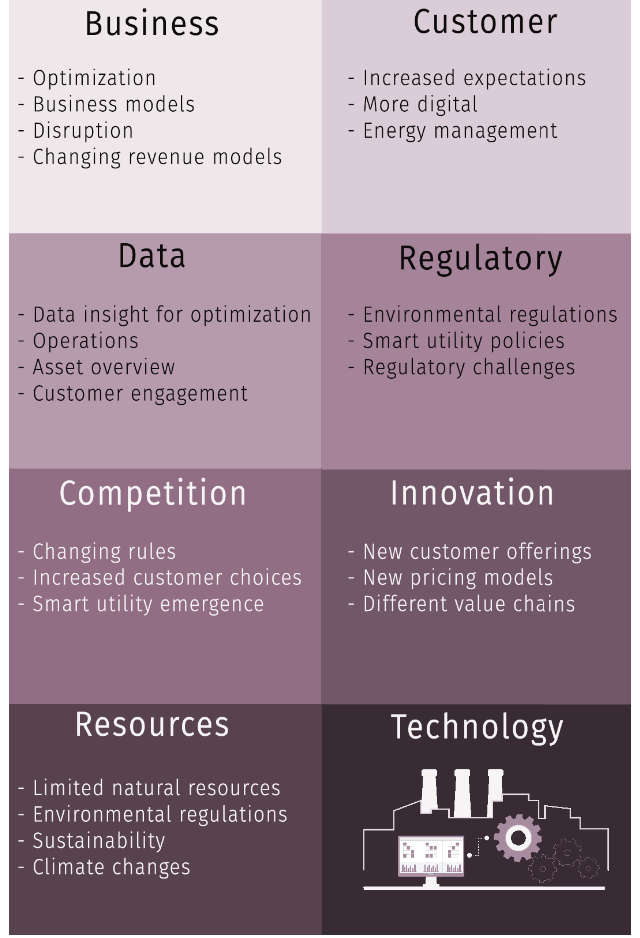


Figure 2.16 How Industry 4.0 influences different sectors

2.3.1 Four pillars

Before starting the project four pillars were identified that will be discussed here. In short, they are:

- Data acquisition (digitization/digitalization)
  - The process of measuring physical objects with a digital medium
- Design automation
  - The integration of self-acting processes within the design process
  - Mainly digital solutions
- Fabrication
  - The process of production
  - From the start of a print to the final (postprocessed) product
- Human machine interaction
  - The interaction of humans with the entire system
  - Interaction with a printer, but also with slicers etc.

The pillars will be discussed further in this chapter. Fabrication will not be handled here, as it has been discussed in chapter 2.2 FDM Printing.

2.3.1.1 Digitization, digitalization and Human machine interaction

Digital transformation is one of the key enablers to change the industry and goes hand in hand with human machine interaction (Irniger, A. 2017). Industrial manufacturers are moving to a digital world (Festo Didactics. 2015). Manufacturing companies are using technology to move from mass production to customized production (Deloitte. 2017).

Difference between Digitization, Digitalization and Digital Transformation

It is important to make a distinction between digitization, digitalization and digital transformation as it was observed that these terms are being used for each other while they each have their own distinct meaning.

- Digitization; All manufacturing used to be analog, sensors make it digital, gathering data from the physical world and making it digital is digitization. (Bloomberg, J. 2018)
- Digitalization; Once analog data has been digitized it's not usable yet. Making the data usable is digitalization. (Ezell, S. 2018)
- Digital transformation; Taking advantage of digitalization to create completely new business concepts. (Irigner, A. 2017)

More elaborate definitions on the digitization, digitalization and digital transformation can be found in appendix H.

Some of the trends that have been identified in Digitization for manufacturers include:

- IOT
- Mass customization
- Robotics
- AI and machine learning
- Improved speed and efficiency
- Data and analytics
- Artificial intelligence in FSM
- AR tools
- Predictive maintenance

These subjects will be discussed in this chapter.

IoT And Industry 4.0

A central principle in this industrial transformation is IoT (Oliver, A. 2018). IoT provides real-time feedback and sends a signal in case of errors or broken products. Utilizing IoT this way already allows for a reduction of cost and waste.

Industry 4.0 represents the interconnected factory where machinery is online, and at the same time is also smart and capable of making its own decisions (Burke, R. 2017). With smart machinery there is also an introduction of a hybrid approach of virtual and actual content warehouses.

Mass customization

Mass customization allows manufacturers to react to consumer demand more efficiently (Geraedts, J. 2018). Customer expect the products they use to be intuitive and easy to interact with, so mobilization and connectedness continue to drive manufacturers to innovate.

Robotics

Industrial robots used to perform pre-programmed, repetitive tasks on the assembly line. The increase in digitization also increases the smartness of robotics, robots are now capable of performing human tasks, with skills like dexterity and memory. Robots that can be trained and work collaboratively with humans do provide a safer working environment, by taking the place of humans in dangerous environments (Wilson, J. 2018). For example, Komatsu has developed autonomous dump trucks for mining sites, that will be able to remove human drivers from this area when implemented (Grayson W. 2018). Machines with sensors provide manufacturers with valuable feedback and data. Sensors can be used to quickly identify mechanical issues, allowing companies to make necessary adjustments more accurately and scheduled (Johnson, G. 2016).

AI and machine learning

Machines adopting intelligent behavior is something that has been around for a while already. The implementation of Artificial Intelligence has the potential to transform the way the manufacturing industry collects information, performs skilled labor, and predicts consumer behavior (Hughes, M. 2018). Quality is no longer sacrificed for efficiency, as machine learning algorithms determine which factors impact service and production quality. Sensors and actuators have replaced human hands, resulting in less wasted time and materials, as well as optimized accuracy and workflow (Johnson, G. 2016).

Improved speed and efficiency

By integrating IT systems, relevant data can be accessed and shared instantly. This facilitates quicker, more collaborative and transparent communication within companies. Cloud computing is growing to be more reliable resulting in manufacturers implementing its software with more confidence (The Economist Intelligence Unit. 2016).

Data and analytics

Digital content is still multiplying exponentially. Big data analysis becomes increasingly difficult and time-consuming as digitized manufacturers struggle to manage, update, and analyze product and consumer information (Arora, S. 2018).

Information on operations, supply, delivery and customer support used to be difficult to find or hard to work with (Arora, S. 2018). In the digital era, that data is streamlined and collaboration-friendly, increasing accessibility for all stakeholders.

Artificially intelligent FSM

With artificial intelligence, field service management (FSM can be optimized to ensure the quickest service is performed by the most qualified technician. By quickly calculating the location where a technician is needed and the location of available service technicians at any given time, and cross-referencing this information with the technicians' skill sets and expertise, AI powered FSM software can dispatch the best man or woman for the job in real-time. (Hoppe, G. 2018)

Augmented reality tools

AI applications do ensure that a technician suited for a task is assigned, but the technician might need added information. A combination of augmented reality tools with a database of video tutorials, manuals, and offsite experts is changing the way field service technicians tackle complex issues and redefining the field service sector. (Porsche tech. 2018)

Predictive maintenance

Sensors programmed to measure temperature, wear and tear and other indicators make machines capable to transmit warning signals in advance of breakdowns and malfunctions when the first signs of degradation appear. This makes it possible to schedule repairs at convenient low productivity times avoiding downtimes (Sciban, R. 2017).

2.3.1.2 Design Automation

The definition 'automation' originates from the Greek word 'automatos', which means self-acting. The meaning of automation itself is therefore the process in an industry where multiple operations are changed from a manual process to a self-acting process (Gupta, A. 2017). With Design Automation, the integration of self-acting processes to the operations within the design process is meant. A typical design process (in this case of architecture) as found in figure 2.17, includes defining the problem (1), collection of data (2), analyzation of the idea (3), development of a solution (4), receiving feedback (5) and improvement of the design (6). Looking back at the original project, the most relevant steps within the design process are numbers two, four and five. The human interaction of defining a problem, creating ideas and complexity of designing or engineering improvement are currently too hard for automation.

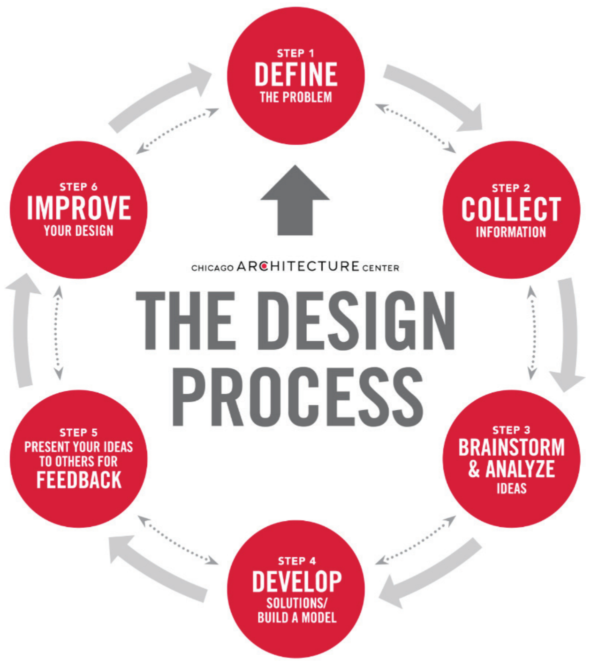


Figure 2.17 Design process (By DiscoverDesign, 2014)

The collection of data for inspiration is a human attribute that is hard to automate. However, the collection of data itself can partly be self-acting. Companies are working on products that constantly collect information for businesses uses. Examples of these are Amazon, Facebook, General Electric and Google, who use machine learning to predict what a consumer might want to have. Personalized advertisements are then shown to the consumer. This automation with machine learning can also be applied to the collection of data. (Gupta, A. 2017)

Presenting a printed product can be automated by showing a digital or tangible model to the consumer. Likewise, by creating standard variables for feedback, the program can decide what the most relevant response is.

Requirements Chapter 2.3.1 Four pillars:

- The physical process is measured in a digital medium
- Self-acting processes are integrated in the design
- Must support an Intuitive interaction between human and machine
  - Assisting human operators in the process
- Must be capable of making its own decisions
- Must have the ability to identify mechanical issues
- Must store data on production parameters
- Must be able to communicate with other machines
- Must have predictive maintenance

2.3.2 Digital twin

Digital twinning is required for FDM-printers to function in Industry 4.0. A digital twin is a dynamic software model of a physical product or software, that, according to Kher, S. 2017 relies on

- Sensor data
- Responds to changes
- Improves operations
- Adds value

It includes a combination of, metadata, condition or state, event data and analytics, Figure 2.18 shows the Digital twin model as proposed by Unity in 2018.

The digital twin is a digital representation of a service, product or process. The digital representations enable digital testing, modeling, simulations and monitoring by using the sensor data of that service, product or process. Data is the output given by a digital twin and by sharing and analyzing this data, companies can make decisions that impact their performance (Kennedy, K. 2018).

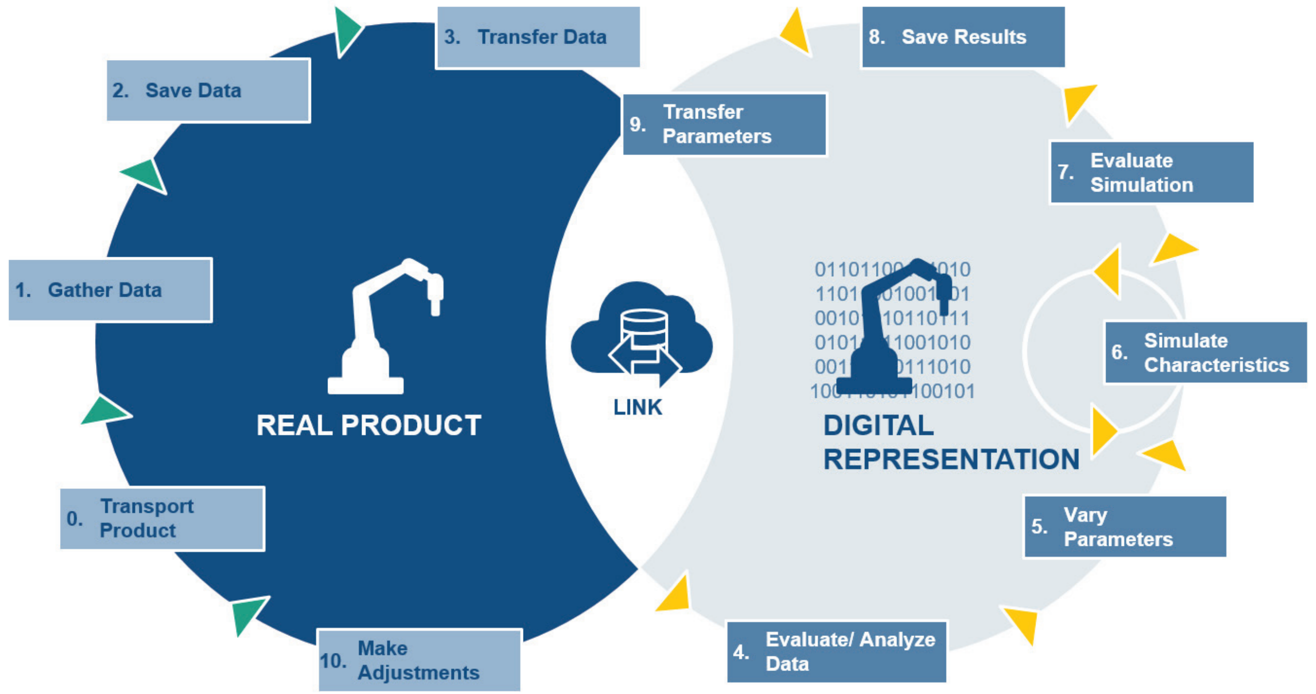


Figure 2.18 Digital Twin model (Unity. 2018)

Requirements Chapter 2.3.2 Digital twin:

- The process must have a digital representation
  - The process must have the ability to be simulated
  - The process must be tested digitally
  - The process must be monitored digitally
- Data gathered during the process must be analyzed autonomously

2.3.3 Design principles

In industry 4.0, 4 main design principles have been identified by researchers (Herman, M. 2016):

- Interconnection (interoperability), Machines, devices and people that communicate with each other
- Information transparency, Information about the costs, effectiveness, speed and best processes are all available to operators and extendable to customers
- Technical Assistance, information systems are designed to support humans in making decisions and solving problems
- Decentralized decision-making, the ability of cyber-physical systems to make simple decisions such as load-balancing on their own

These principles have been found to be key enablers of industry 4.0 and machinery designed for the industry must include these principles.

Requirements Chapter 2.3.3 Design principles:

- Must have the ability to communicate with other machines, devices and human operators
- Information about the costs, effectiveness, speed and best processes must be available to operators
- Must support humans in making decisions
- Must be able to make decisions

2.3.4 AM in Industry 4.0

The creation and commercialization processes are made digital in the Industry 4.0 concept (Dalenogare, L. 2018), there are some parts in the process however, that are not yet. In their 2017 report, SmartTech found that 3D printing in manufacturing is the most labor intensive, making it the primary bottleneck in a more streamlined, efficient and sustainable idea of production. They proposed the workflow presented in figure 2.19.

Within the workflow several different phases and levels where automation could be implemented can be found. In some of these cases the means to do so already exist and only need to be assigned or programmed for specific tasks, in other cases, they still need to be developed. All 3D printer manufacturers have become aware that, as AM becomes a more efficient mass manufacturing or mass customization platform, the 3D printer is no longer a stand-alone system but needs to be integrated into so-called “production cells” or “end-to-end digital production lines”. (Sher, D. 2018) These production lines include several different stations, which can also be integrated into single systems, with automation occurring at three levels.

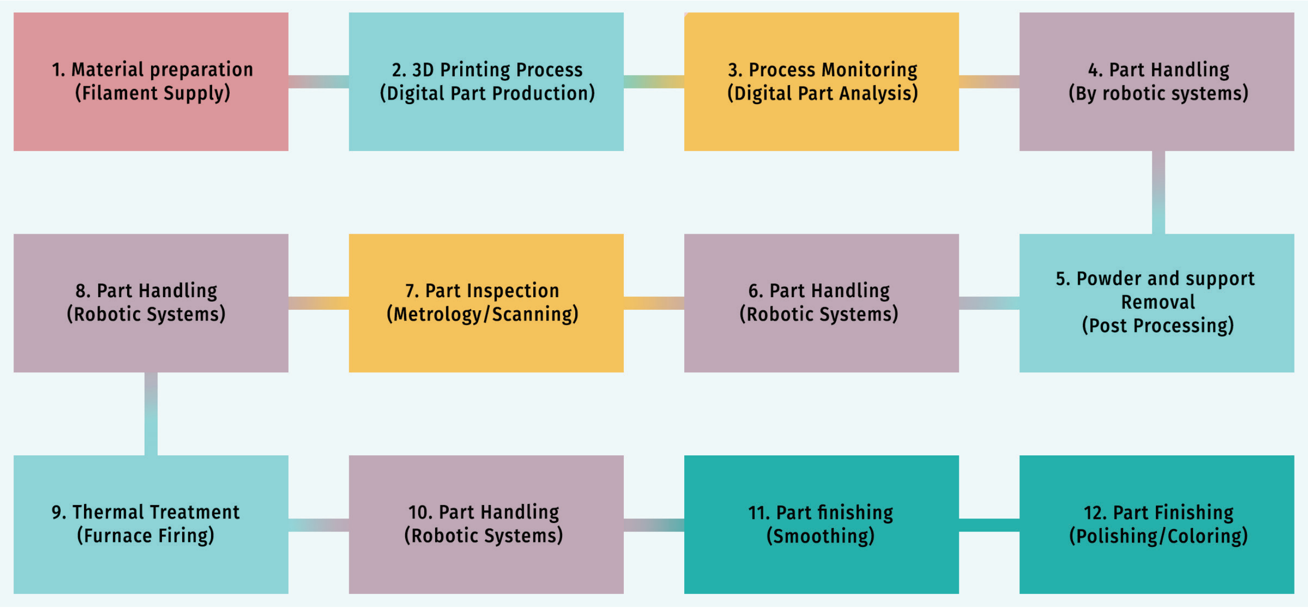


Figure 2.19 3D print Workflow (as proposed by SmartTech)

The first is software, where Manufacturing software is being optimized for AM. The second being within the different processes (3D printing, material handling, post-processing, finishing) and the third in the overall AM workflow automation where robotic systems and electronics act as a connection to the different stations.

Companies working towards Industry 4.0

Most of the major AM technology companies are working toward the automation and preparation for industry 4.0. With some more ambitiously than others. Concept Laser is a good example in this. They have outlined a clear vision for the fully automated factory of tomorrow (Concept Laser, 2017). Other metal AM system manufacturers such as Renishaw (Renishaw, 2018) and Additive Industries (Additive Industries, 2017) have introduced production systems providing integrated and automated powder sieving and resupply, thermal treatment and even part handling. EOS also provides solutions for both process and workflow automation. HP’s entry and target to produce high-speed laser 3d printers (Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS)) with their Jet Fusion printers has been driving current market leaders like EOS and 3D Systems to focus more on optimized and automated workflows and new systems (ALL3DP, 2017).

The manufacturers of desktop printers such as Ultimaker, Formlabs, Lulzbot and MakerBot are building automated production cells and networked 3D printer farms which in their turn drove Stratasys to build three different solutions including robotic arms and multiple 3D printing engines for increased automation and production rates through 3D printing (Stratasys, 2017). Siemens software is often found in these automation solutions (Siemens 2018). Appendix I contains additional examples of companies that are implementing Industry 4.0

Key enablers for serial production of additive manufacturing within a production line as identified by EOS:

- Automation ready
- Increase of productivity
- Increased reproducibility
- Scalability
- Monitoring
- Production integration

Requirements Chapter 2.3.4 AM in Industry 4.0:

- Integrated into so called “production cells” or “end to end digital production lines”
- Must be automation ready
- Must increase productivity
- Must increase reproducibility
- Must be scalable
- Must integrate production

2.4 Trend analysis

A DEPEST method has been done to identify relevant trends for additive manufacturing and industry 4.0. The most relevant ones have been summarized in this chapter while the complete DEPEST can be found in appendix J.

2.4.1 Demographic

These trends address the composition of the population.

The world population is still increasing. It increased from 2.5 billion in 1950 to 7.3 billion in 2015. Predictions are very versatile, in the average variant it will increase further to 9.7 billion in 2050 and 11.2 billion in 2100, if current trends do not change it will even be 10.2 billion in 2050 and 19.3 billion in 2100 (EEA. 2016).

In the EU the increase will be limited, from 505 million people now to 510 million people in 2030 and then decrease to 465 in 2100, age structure will shift drastically, 19% is 65 or older now, this will be 30% in 2050 and 43% in 2100 (EEA. 2016).

A report by Harris, B. proposes that migration can play an important role in the population dynamics within the EU member states, but it is unlikely to reverse the overall trend of population ageing.

2.4.2 Economic

These are the trends found that have to do with economic growth, inflation, purchasing power, etc.

An increasing number of 3D printing users have their own 3D printer, 44% of professionals that were 3D printing in 2017 had their own printer which increased to 66% in 2018 (Zeijderveld, J. 2018).

AM is changing how products are designed, developed, manufactured, and distributed. By 2021, the 3D printing market could be worth €9.6 billion (PricewaterhouseCoopers. 2018).

The current economic trend of economic growth in the EU is estimated to continue. Consumer spending has been the most important factor for this growth. It is expected that industrial manufacturing, automotive and consumer markets will contribute the most to European GDP's in the following years. The highest growth rates have been estimated to be in the services sector, technology, media and entertainment and financial services (PricewaterhouseCoopers. 2018).

2.4.3 Political/judicial factors/standards

These are political measures at a decision-making, provincial and municipal level.

Attempts for a standardization of additive manufacturing are being made. Standards, specifications, and related conformance and training programs, are integral to this process and are a key enabler for the large-scale introduction and growth of AM (ANSI. 2017).

AM is raising challenges, especially concerning civil liability and intellectual property rights. Legislative and regulatory recommendations in the field of 3D printing have been written and published. It is uncertain who should be liable when a 3D printed product is found to be defective or unsafe. Clear rules on who owns the right to a 3D printed product have not been made yet but are needed to protect the work of designers and engineers (European Parliament. 2018).

2.4.4 Ecological

This includes all factors in the area of the physical surroundings and the environment.

With current manufacturing technologies, consumer products are made in high volume, parts are stored, products are produced, stored again, before being distributed. AM decreases the need for warehousing of extra inventory as products can be made on demand (SCW3D. 2018).

Global waste management has been neglected over the past decades. Plastic has been improperly discarded into the natural environment. Circular economy enforces eco-design, waste prevention, recycling and energy efficiency, which helps tackle the environmental pollution problem. Designing eco-friendly, easily recyclable and energy efficient products by using fewer resources would enable manufacturing durable goods that could be recycled into quality recyclables (EUROPEAN ENVIRONMENT AGENCY, 2018).

Weight reduction through part geometry optimization. This can only be produced cost-effective through the use of additive manufacturing resulting in a potential reduction of emissions from airplanes and cars by requiring less weight to be transported (Boissonneault, T. 2018).

2.4.4 Social/cultural/industrial

These are characteristics in the area of people's perception and how they look at various technologies (FDM printing in this case).

In a research by Sculpteo (with over 1,000 respondents from a variety of industry segments) a major shift in the level of expertise of the respondents was found (Figure 2.20). Their research, performed in 2018, found that 15% of the correspondents see themselves as beginners, 41% intermediate and 44% as experts which is an increase over 2017.

The respondent's top priorities for choosing 3D printing were: 39% accelerating product development, 25% to offer customized products and limited series (which was 16% a year before) and 19% had production flexibility as their top priority.

The emphasize on customized products and limited series will increase with 26% of

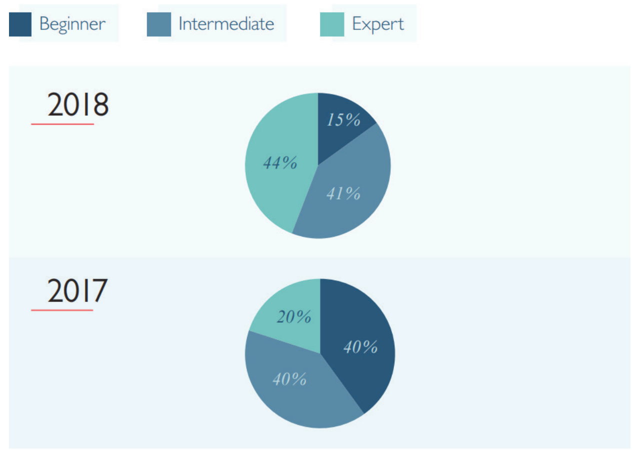


Figure 2.20 When it comes to 3d printing, you consider yourself to be? (Results by Sculpteo)

the respondents expecting to make this a top priority. An increase in experts in the field of 3D printing and new ways of applying 3D printing will be key. (Zeijderveld, J. 2018)

Over the past years, terrorist organizations destroyed important works of art. This initiated artists, archeologists and non-governmental organizations to team up and remake, replace and protect the art for future damages. 3D scanning and printing technology has been used to rebuild and recreate priceless artifacts (Boissonneault, T. 2018).

3D printing is also being used for

education and making art and historic artifacts available for those who are visually or motion impaired. In fact, 3D printing service provider Materialise recently 3D printed a full-size mammoth (Boissonneault, T. 2018).

Ultimaker observed a shift in Cura usage from weekends to weekdays. Meaning there is also a shift from home use to professional environment (Ultimaker. 2017).

2.4.5 Technological

This is about all developments and innovations an organization has to respond to in order to keep up with the times.

Printer farms are increasing in popularity. Different parties are doing so, each with their own vision. Stratasys introduced an entirely new concept where Ultimaker does it more on a software level with Cura connect (3D Print Magazine. 2018).

FDM printer industry is still rapidly growing, an exponential increase in the manufacturing industry is expected (3D Print Magazine. 2018). Chemical companies have entered the AM market giving a momentum of 3D printing with alternative plastics pushing the movement from prototyping to production further.

New in the field of FDM printing are 5-axis FDM printers, opening new possibilities, complete with automatically changeable printheads (Verashape, 2018).

In the high-end spectrum of FDM printing, developments are made as well. Stratasys has produced aerospace versions of their printers, ULTEM is being used to print parts of airplane interiors. To do so, machine, material and process have received the necessary certifications (3D Print Magazine. 2018).

The focus will turn more towards streamlining pre- and post-production processes as finishing is labor and cost intensive (Materialise. 2018).

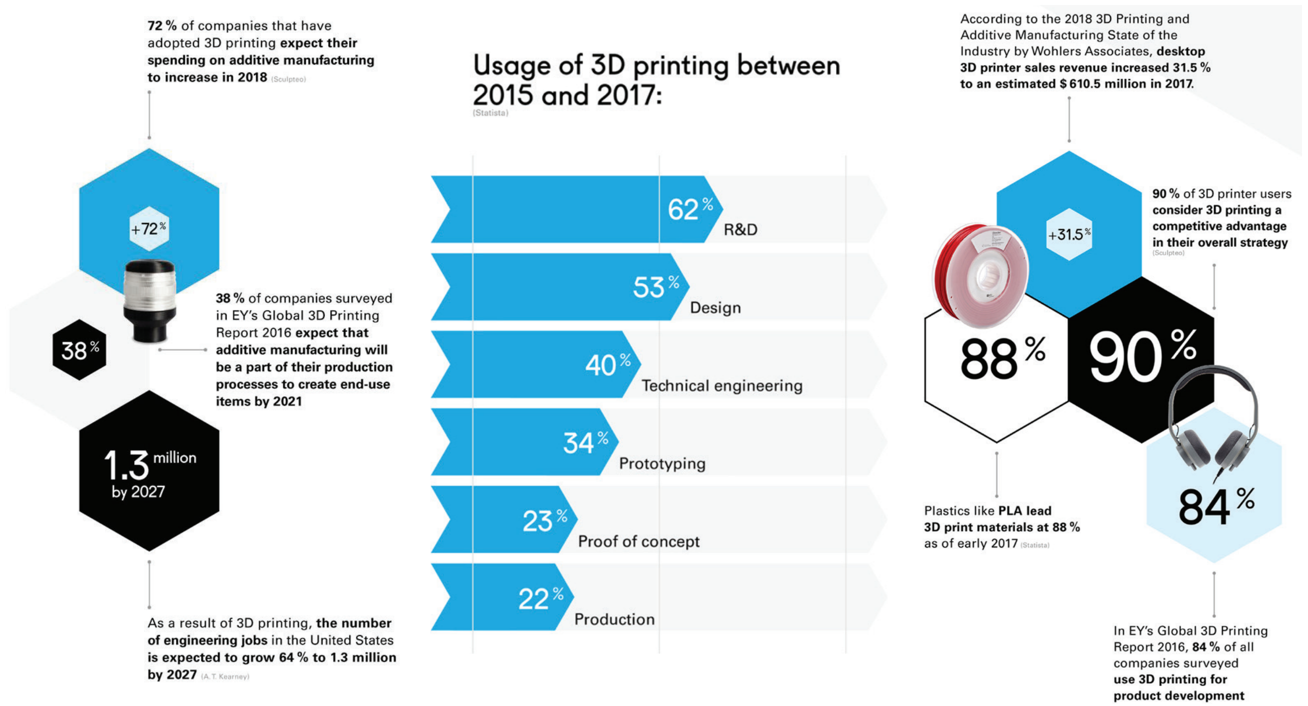
Industrial automation in the form of pick and place robotics is used to drastically raise the efficiency of the post-production time and cost, in combination with good software there is the ability for automated post-production systems (Materialise. 2018).

Simulation software will play a role in predicting failures before they happen (Materialise. 2018).

More integration of 3d printing in existing supply chains.

Collaboration between existing players in the field of hardware, software and service providers, leading to an optimized and easier-to-integrate product offering (EY Global. 2016).

More collaboration between industry and consumer, e.g. co-creation.



Figures 2.21 A-B-C Statistics of applications (as seen by Ultimaker)

The statistics in figures 2.21 A, B and C show the level of use for various applications of 3D printing, between 2015 and 2018. According to this latest survey, conducted in 2018, 41% of the professionals who use 3D printing said they did so to create proof of concepts.

84% of the companies surveyed for EY's Global 3D Printing Report 2016 reported using 3D printing for product development, with 38% expecting that additive manufacturing would become a part of their production processes to create end-use items by 2021. (EY Global. 2016)

Requirements Chapter 2.4 Trend analysis:

- Must be able to be adjusted to standards, specifications, related conformance and training programs that are to be defined
- Must come with a waiver of liability for copyright infringement
- Must come with a waiver of liability for defective/unsafe prints
- Must be able to produce customized products
- Must offer production flexibility

2.5 Workflow

To make a foundation to the system and summarize the analysis, 2 workflows have been made (Figures 2.22 and 2.23)

On a basic level the 3d printing workflow goes as follows:

- Designer comes up with an idea
- 3D model is created in CAD or other modelling software of choice
- 3D model is then translated to a mesh file, most commonly an STL or OBJ
- Mesh file is checked for errors and “printability” through NetFabb or other file checking services
- Mesh file is then put into a slicer software
- Slicer software translates the mesh file to a layer-by-layer toolpath with specific machine settings, named GCode
- Gcode or a gcode equivalent runs on the machine and the model gets printed
- Model is removed from printer and prepared for post-processing
- Post processing (support removal, smoothening, painting)

In the workflow of industry 4.0 the operations are analyzed on a physical and digital level. Human interaction has been added for FDM printing as well to identify the touching points of human operations.

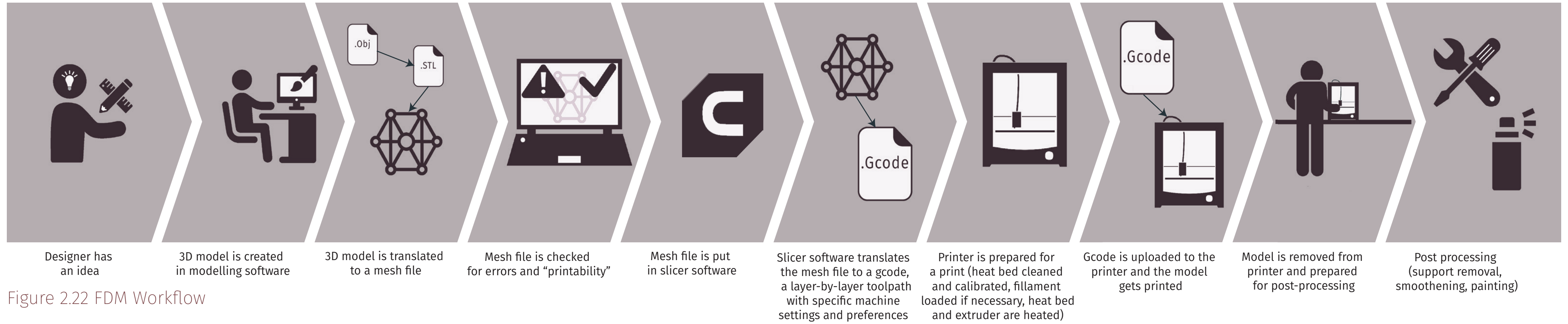


Figure 2.22 FDM Workflow

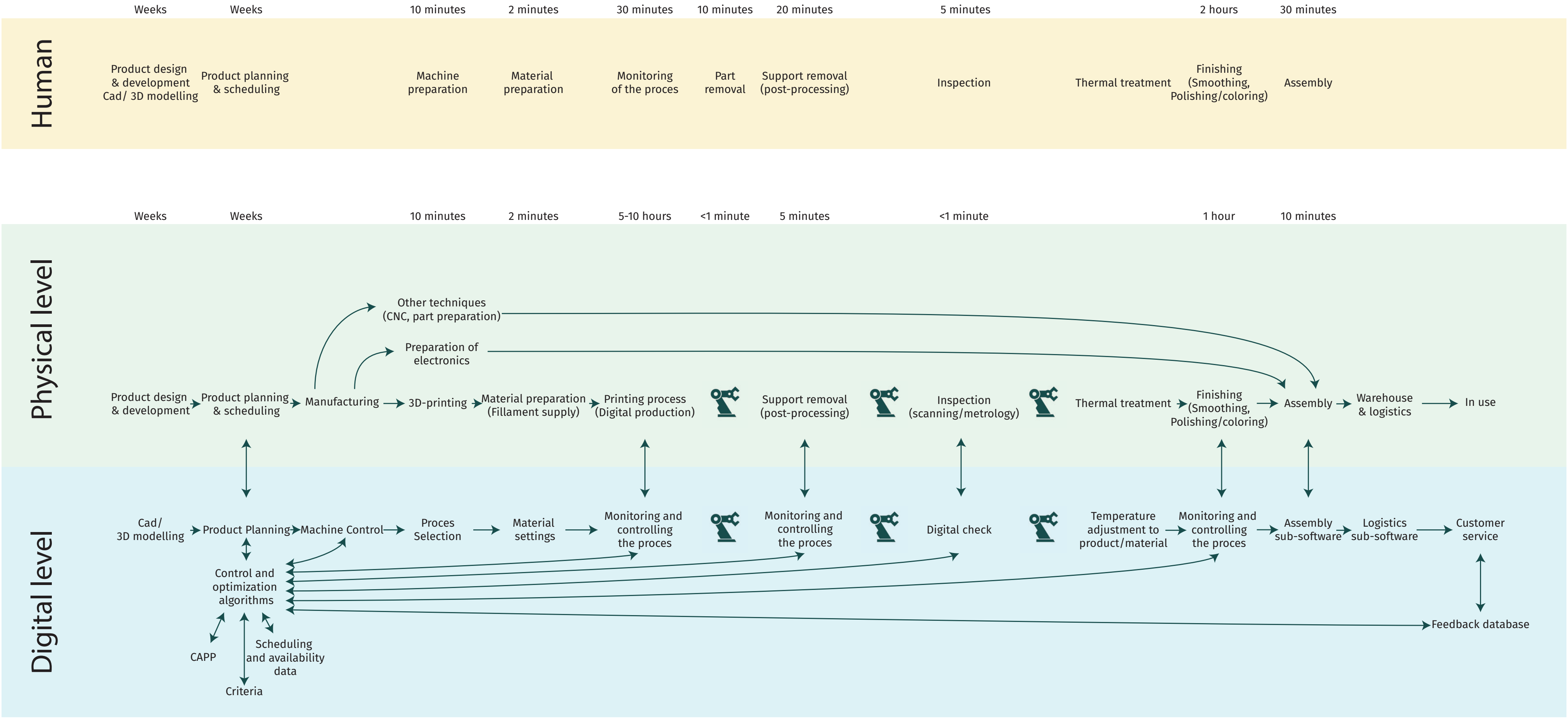


Figure 2.23 Industry 4.0 Workflow

2.6 Analysis conclusion

The requirements found have been bundled (2.6.2) to conclude the analysis. From this list a set of design drivers for the project have been selected, which can be found in 2.6.1. The Design drivers will be used as a starting point for the ideation phase.

2.6.1 Design drivers and opportunities

The design drivers follow from the requirements and insights found during this analysis. They have been identified to be enablers for FDM printing in industry 4.0.

- Create a more autonomous process by reducing the human necessity
- Deliver a complete package
- Have a scalable system
- Communicate with the rest of the factory (other machines, devices and human operators)
- Increasing product throughput
- Controlled printing parameters

2.6.2 List of Requirements

To make a feasible design for FDM printers that are integrated within industry 4.0, certain requirements need to be met. A list of requirements was initially created in accordance to Roozenburg en Eekels (1998) method of making a list of requirements, which can be found in appendix K.

To conclude the analysis, the requirements of the chapters are summarized in the list below. The requirements aim to decrease the labor intensity of FDM printing while also conforming to the 4 core-principles of industry 4.0. (as mentioned in chapter 2.3.3). The concept that will be proposed in this report will need to match these requirements, the requirements mentioned in appendix K will be used as a guideline in the design process but the list below is leading as it follows directly from the insights found in the analysis.

- Must offer a complete package
- Must be able to access the Cura material database
- Fits in the professional product category of the competitor diagram
- Decreases idle time of the printer
- Must be able to work with a wide range of materials
- Must be able to support new and improved materials
- Must be able to combine printing material with support material
- Must be able to print engineering grade materials
- Materials must be stored in optimal environment (dry)
- Must have a strong adhesion during printing
- Part can be released after printing is finished
- Printing surface matches the material that will be used for printing
- Must have a standard accuracy of ±0.15% (lower limit: ±0.2 mm)
- Must be capable of printing with a layer thickness in a range of 0.1 – 0.25 mm
- Must have a heated chamber for controlled printing parameters
- Must be capable of printing with a minimum wall thickness 0.7 mm
- Must have a build envelope of 215x215x200/ printing unit
- Must be capable of dual extrusion, second extruder for water-soluble support
- Maximum cost of €10.000 per printing unit
- Prints must leave the printer without human interference
- Must be able to combine multiple printing units
- Must increase throughput of parts
- Must have the option to monitor the process autonomously
- Must detect errors
- Must have an automatic first layer calibration
- Must increase the printer uptime
- Must decrease human intervention for
    - Fixing failures
    - Order preparation
    - Loading filament
    - Software preparation
    - Part removal
    - Cleanup
    - Monitoring
    - Calibration
- Must increase automation in the workflow
- Must combine the power of multiple extruders, to increase production
- Must not need new tools to change printed product
- Must maintain the freedom of complexity
- Must maintain a flexible system, where upgrades and updates can be added
- Must allow for post processing
- The physical process is measured in a digital medium
- Self-acting processes are integrated in the design
- Must support an Intuitive interaction between human and machine
    - Assisting human operators in the process
- Must be capable of making its own decisions
- Must have the ability to identify mechanical issues
- Must store data on production parameters
- Must be able to communicate with other machines
- Must have predictive maintenance
- The process must have a digital representation
    - The process must have the ability to be simulated
    - The process must be tested digitally
    - The process must be monitored digitally
- Data gathered during the process must be analyzed autonomously
- Must have the ability to communicate with other machines, devices and human operators
- Information about the costs, effectiveness, speed and best processes must be available to operators
- Must support humans in making decisions
- Must be able to make decisions
- Integrated into so called “production cells” or “end to end digital production lines”
- Must be automation ready
- Must increase productivity
- Must increase reproducibility
- Must be scalable
- Must integrate production
- Must be able to be adjusted to standards, specifications, related conformance and training programs that are to be defined (Appendix I)
- Must come with a waiver of liability for copyright infringement
- Must come with a waiver of liability for defective/unsafe prints
- Must be able to produce customized products
- Must offer production flexibility

3. IDEATION

This chapter reports on the ideation phase. The work in this phase has been ordered in sub-chapters making it look like a linear process, while in fact all these subjects have been done in a circular design process. The ideation phase consists of a diverging process, with ideating and brainstorming, and ends by converging into concepts. Chapter 3.1 will start with the chosen design direction followed by the part about gaining inspiration in 3.2. A first set of idea's was made (3.3) by looking at the design drivers (2.6.1). Brainstorming sessions and ideation (3.4), in accordance with the list of requirements (2.6.2) eventually led the creation of two concepts (3.5).

3.1 Design direction

To choose a well-founded design direction, insights from the analysis, sessions with experts and interviews were transposed to directions which in turn were clustered. It was possible to divide the drafted design directions into four clusters; Smart machines, Interaction with the system, Human help and Triggers. A list of these Directions and the insights that led to these directions can be found in Appendix N. From this list the direction, "How do you decrease human necessity in FDM printing?" was chosen as it was the direction with the best potential for FDM printing in the industry. It is however, not good enough as it does not include industry 4.0. The design direction was rewritten and became the following.

Decreasing the labor intensity of FDM printing by answering the question:

"How can FDM-printing techniques be integrated in a production line by applying the core design principles of industry 4.0?"

In order to be applied in an industry 4.0 production line, the FDM-printer will have to suffice with the core design principles, which have been defined as:

- Decentralized decision-making, the ability of cyber-physical systems to make simple decisions on their own.
- Interconnection, interoperability, machines, devices and people that are capable of communication among each other.
- Information transparency, information about the costs, effectiveness, speed and best processes are all available to operators and can be extended to customers.
- Technical Assistance, information systems are designed to support humans in making decisions and solving problems.

The design direction resulted the following questions and ways to approach the tasks:

- How can FDM be included in a production line? (Figure3.1)
- Look at this from a bigger picture, start with the entire line and then look towards printing.
- Approaching companies and experts that apply FDM techniques within their production, 10XL, YES!Delft, professors at the TU Delft
- How can decentralized decision-making be implemented within the production line?
    - What kinds of situations will appear and are relevant?
    - What types of decisions have to be made?
    - What kind of strategy is required of the machines?
- What is the optimal way to implement interconnection?

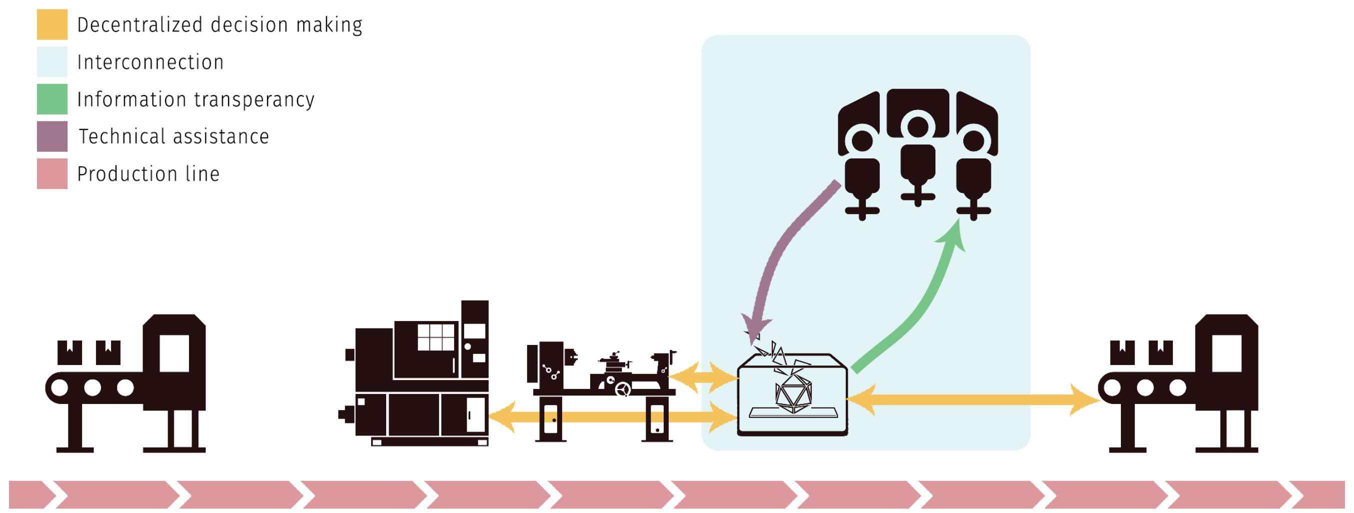


Figure 3.1 FDM printing in a production line

- Which data streams are present?
- Which streams are relevant to link together?

- How can you acquire information transparence to the operator?
  - How is the information gathered?
  - What information is relevant and needed by the operator?
  - What is the best way to pass the information towards the operators?
- How can technical assistance help to support humans when they make decisions and solve problems?
  - First identify the strategy, to find what help is required of machines for humans.

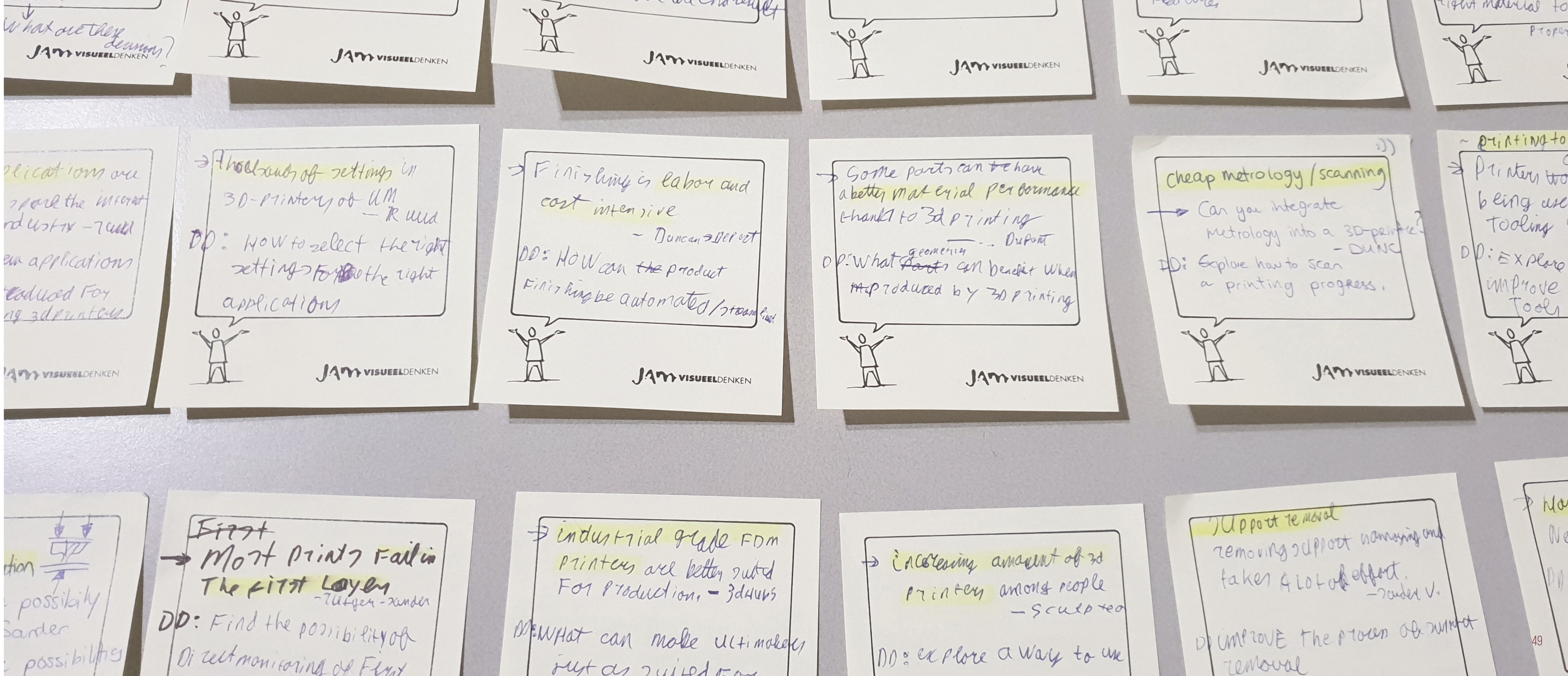


Figure 3.2 Setting up design directions

3.2 Gaining inspiration (Diverging)

With the analysis as a base it was possible to gain more information and especially inspiration with other research method. Trends and insights were found and listed. To gain further knowledge and continue with ideation, interviews (3.2.1) and a creative facilitation session (3.2.2) were held.

3.2.1 Interviews

Multiple experts were interviewed throughout the project. They helped in gaining a better understanding of the subject, the limitations, the benefits and the issues. 7 extracts of those interviews can be found in Appendix E. These are with R. Schönfeld who was responsible for a print farm at the faculty of Industrial design engineering. J. Smith who was one of the first professional filament producers for FDM printing in the United States. Later in the process, towards the embodiment phase there were also interviews with; Erik Tempelman, Associate Professor at the faculty of design engineering (TU Delft), specialized in materials and manufacturing methods. Bas van Deursen, Manager process & materials team at Ultimaker. Johan Versteegh, Research and development team at Ultimaker. Sanne Marx, software/algorithm engineer at Ultimaker and consultant at Alten. Jaime van Tessel, Cura software team. Input of various other experts has been used to validate parts of the project.

3.2.2 Creative Facilitation Session

A creative facilitation session was held to get inspiration for the brainstorming sessions (figure 3.3) that would follow and gather as much ideas as possible in a short time. The entire program of that session can be found in Appendix O as well as the posters made. The session was useful as it gave some new inspiration to use later on in the project.

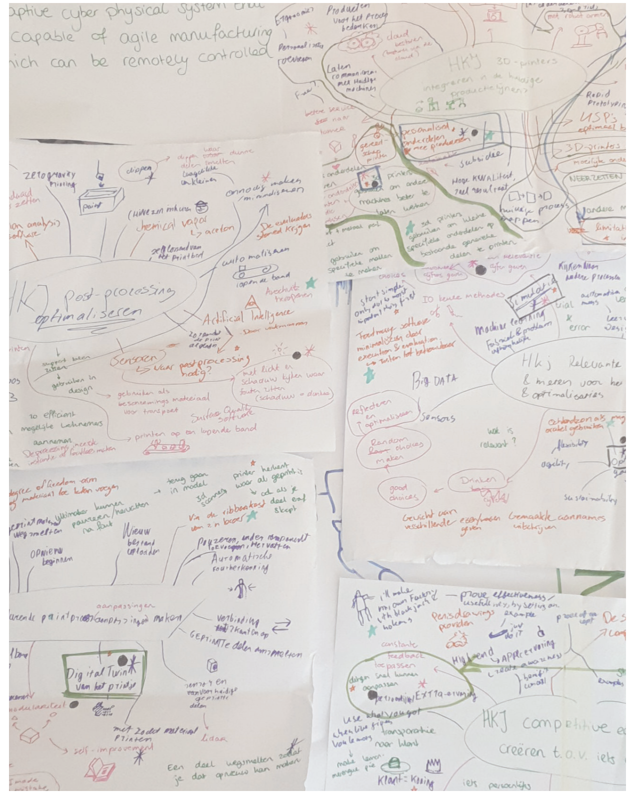
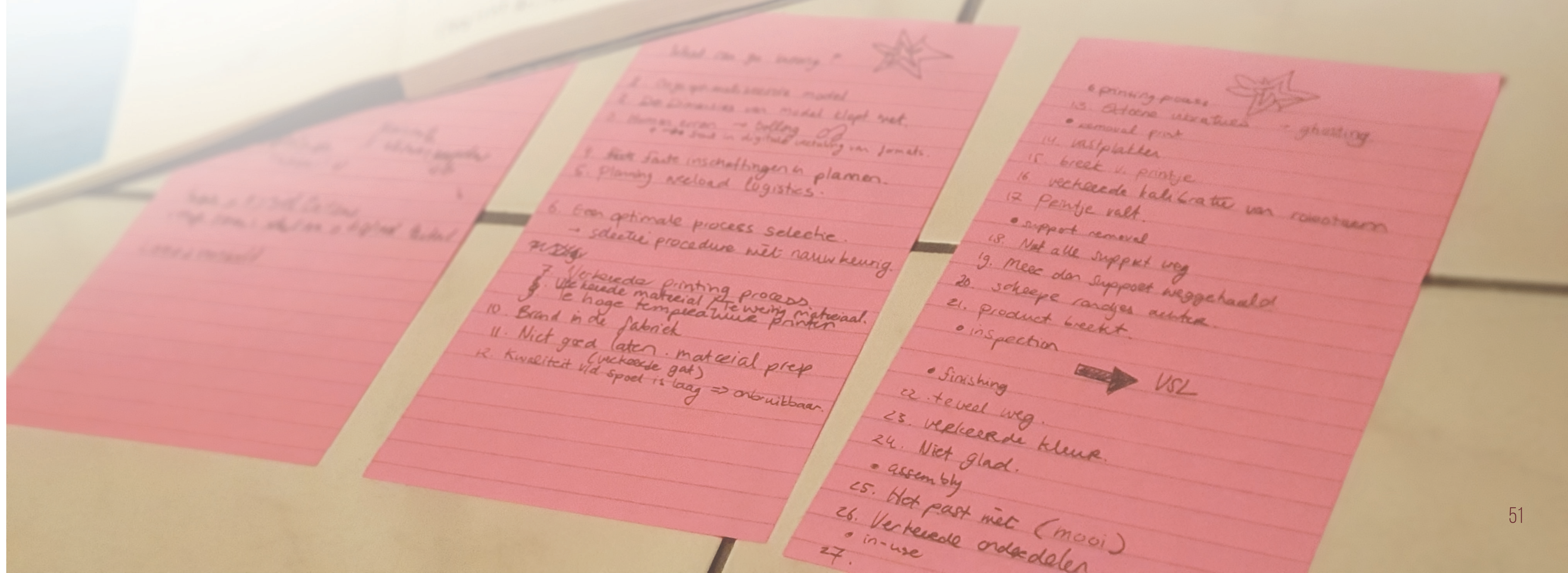


Figure 3.3 Creative Facilitation Session

3.3 First possible solutions

An initial ideation round was done by looking at a production line with FDM printers in it, going through the entire workflow (chapter 2.5) and analyzing everything that can go wrong. The list in appendix P summarizes some of the ideas found. This way of ideation doesn't help to find new ground-breaking ideas, but it does work to get familiar with the subject and start thinking about it quickly. Figure 3.4 illustrates how this was done.

Figure 3.4 First possible solutions



3.4 Brainstorming

The brainstorming was initiated by looking at production lines and Industry 4.0, the goal was to work from the outside in. So, starting with an industry 4.0 factory and working towards the FDM printing system. However, it soon became clear that this wouldn't work as the practical know-how and experience wasn't present and companies claiming to be specialized in Industry 4.0 were not able to assist. In order to keep making progress it was decided to start brainstorming on the improvements of single FDM printers. By identifying the shortcomings to enter the industry with these machines and the interactions a technician has with a printer. With the ideation on single printers done, the ideas were combined and scaled to an industrial level, where new problems could be analyzed and solved.

3.4.1 How-to's

How to's were set-up for the ideation (Figure 3.5), the design drivers defined in 2.6.1 along with a list of steps that can be automated in the printing process were used to create the HKJ's. The full list of HKJ's can be found in appendix Q.

These were combined in a chart found in Figure 3.6 to make initial solutions in the automation of FDM printers.

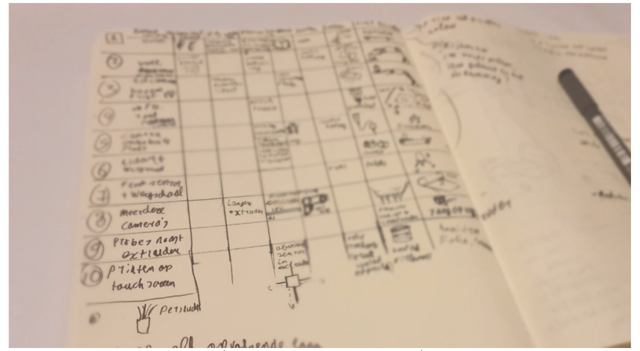


Figure 3.6 HKJ Chart (morfological chart)

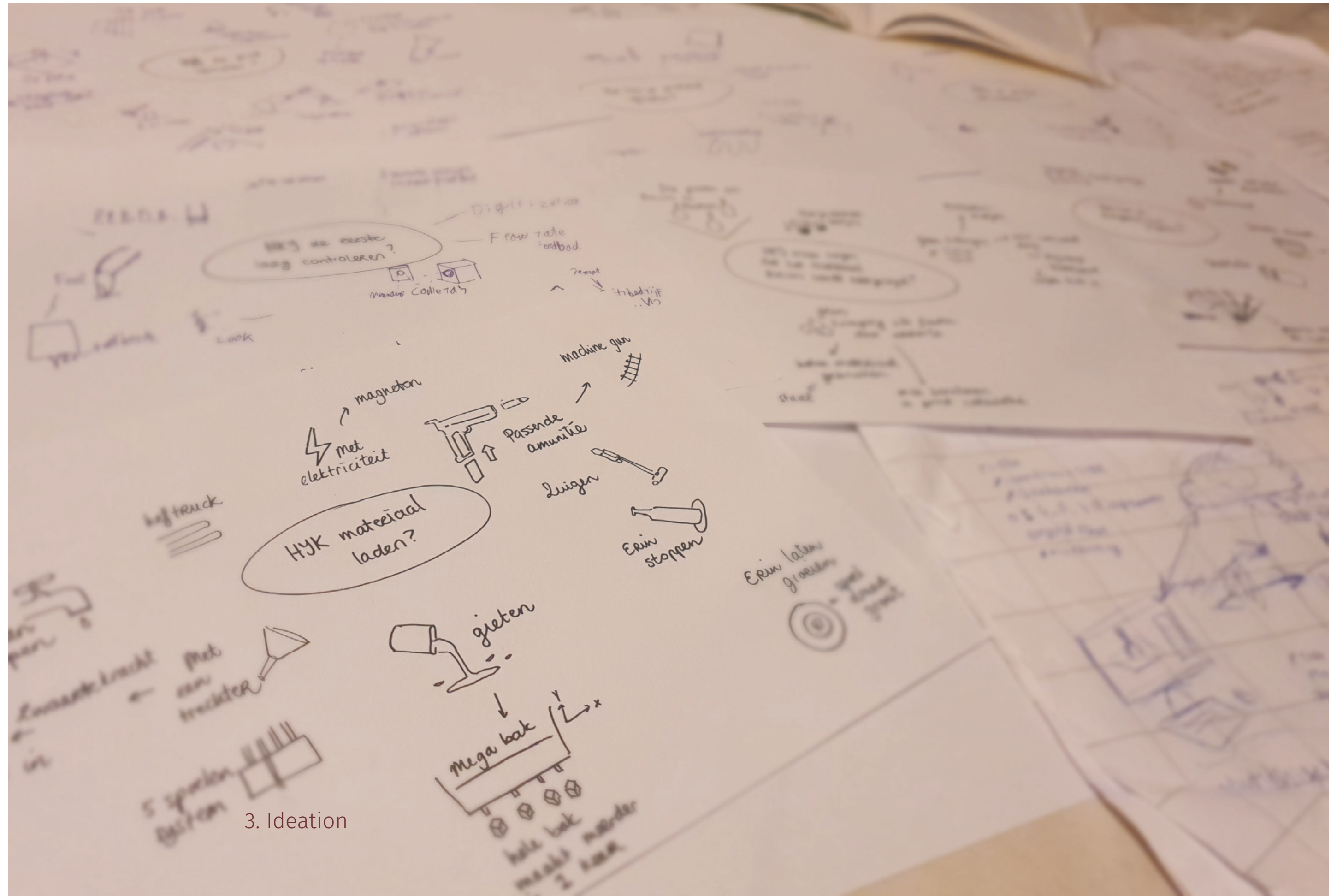


Figure 3.5 HKJ's

3.4.2 Ideas (single printer)

The combinations in the chart of figure 3.6 lead to 10 idea's, that were combined to deliver a solution for the automation of FDM printers. There were various iterations done on these ideas. The worked-out ideas (how they came out after the iterations) can be found in Figures 3.7-3.16. The first step with the ideas is to scale them to a print farm level and then add the core principles of industry 4.0. These will then be used to design the concepts (chapter 4).

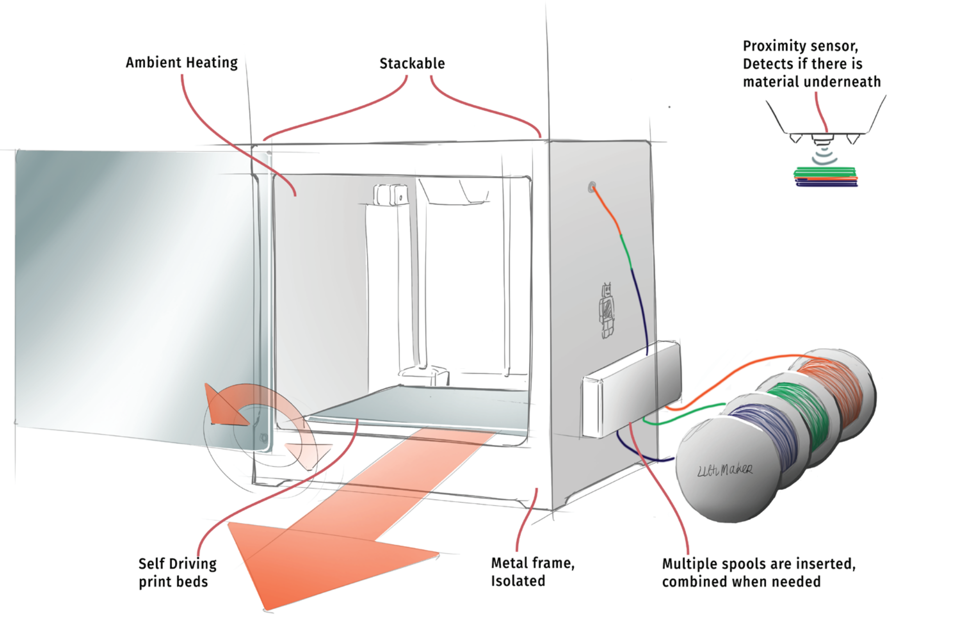


Figure 3.7 Single printer ideation #1

The design features a stackable frame, so multiple printers can be placed on top of each other to increase productivity. The printbed is able to 'drive' out of the printer, so a next bed can be loaded directly after. Filament is combined outside the printer. This way, when a spool runs out of material, the next spool is loaded automatically, decreasing downtime. The printing chamber is heated for more controlled parameters, the door twists open sideways so less space is needed and a conveyor belt can be placed in front of the printer. A proximity sensor in the extruder is used to verify material is placed where needed.

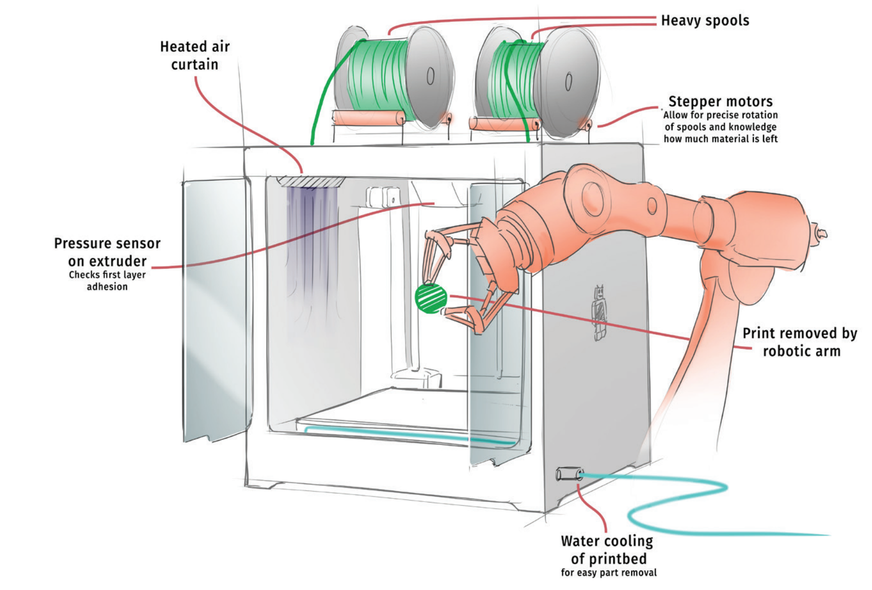


Figure 3.8 Single printer ideation #2

A heated air curtain maintains the inside temperature when the doors are opened. Heavy spools with stepper motors in the holders allow for a higher uptime, as they have to be replaced less often. A robotic arm removes the need for an operator to remove the prints, as they are automatically removed as soon as the printer finishes. The printbed is cooled with water as soon as a print finished, this makes print removal easier.

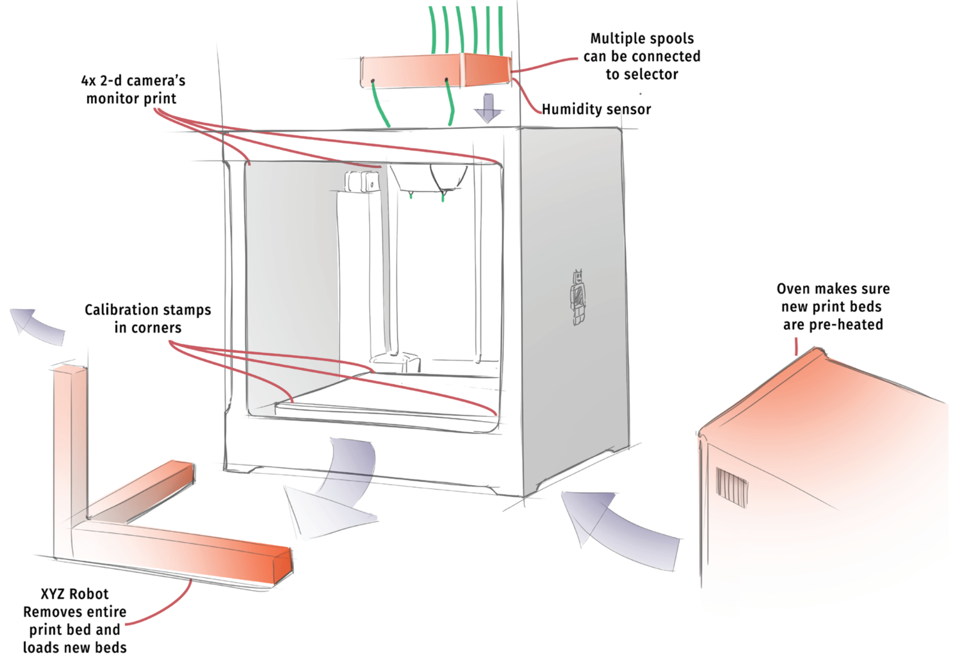


Figure 3.9 Single printer ideation #3

Printbeds are heated in an oven next to the printer, so this does not have to happen before a print starts, saving time in the overall process. An XYZ robot loads the printbeds. Before printing, calibration stamps are printed in the corners of the printbed, 4 cameras monitor the process and use the stamps as reference points. Filament is loaded with a selection system to which multiple spools can be connected. If a material runs out the feeder selects another slot and continues printing. This system contains a humidity sensor as well, to verify the quality of the filament and look for any inconsistencies. The XYZ robot removes the printbed when a print is finished, so the printer can immediately initiate the next print.

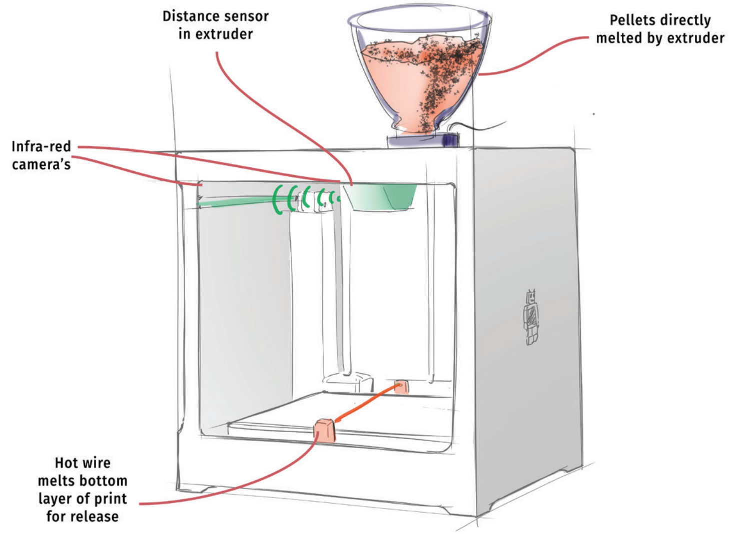


Figure 3.10 Single printer ideation #4

Printer #4 extrudes material directly from pellets. This saves a step in the entire process as filament does not have to be made anymore, making the material cheaper. Another advantage of direct pellet extrusion is the fact that the container can be topped up, making it so that the process does not need to be paused to replace the material. A distance sensor in the extruder head is used to monitor the location of the extruder and therefor measure whether it is in the right place in accordance with the Gcode, infrared cameras measure whether material if placed correctly. When a print is finished, a hot wire melts the bottom layer of the print to release it.

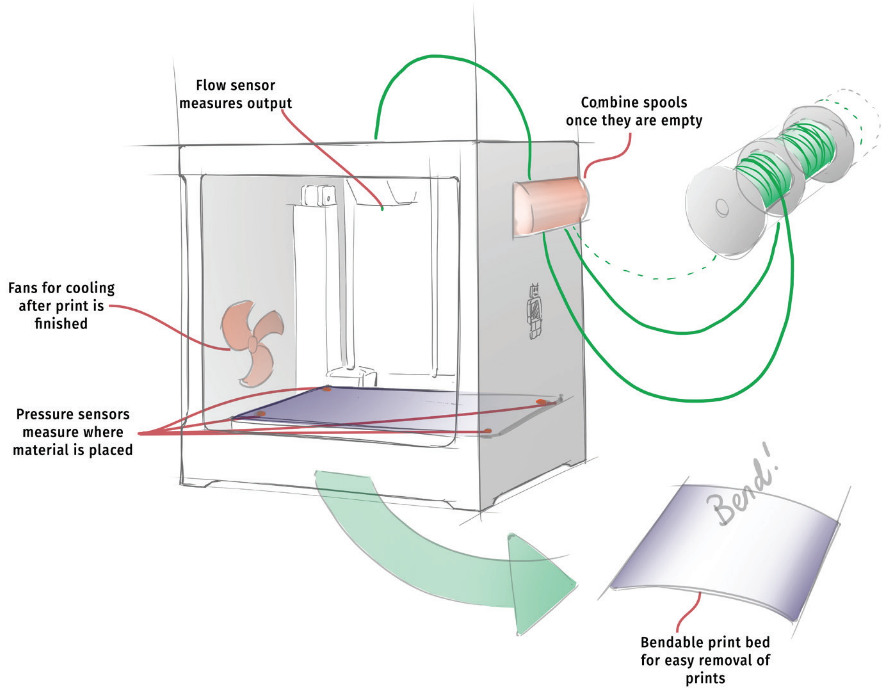


Figure 3.11 Single printer ideation #5

Spools are combined in the same way as printer #1 does. A flow sensor in the extruder, combined with pressure sensors underneath the corners of the build plate measure whether the right amount of material is placed at the correct location. When a print is finished, a fan cools the surface for easier removal. The printbed is made from a flexible material (spring steel sheet) to easily remove the prints from the surface.

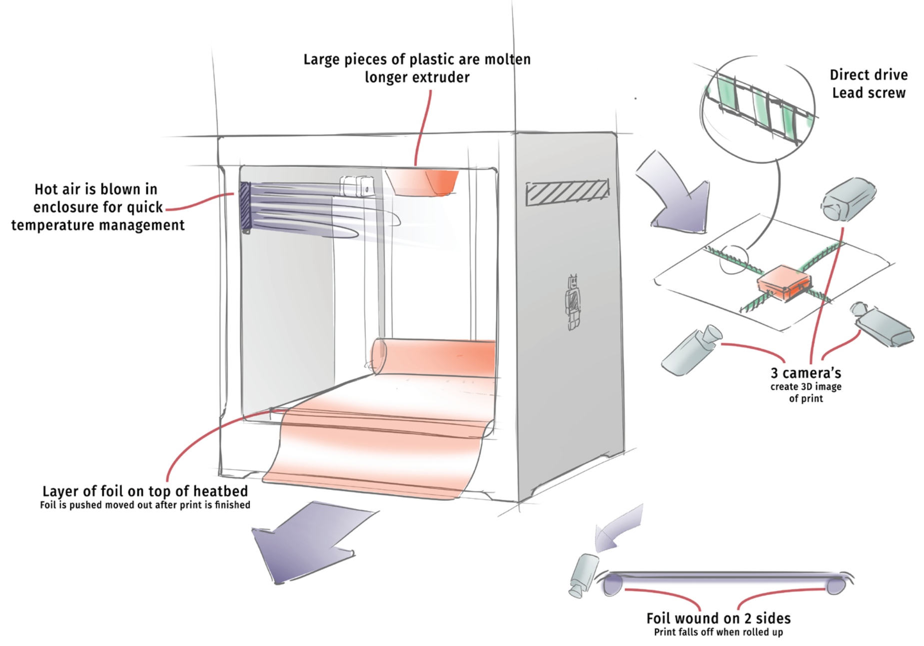


Figure 3.12 Single printer ideation #6

Large blocks of plastic are molten as opposed to strings of filament. A longer extruder is therefor needed as more heat is needed to melt the blocks. The extruder will be heavier than current extruders, so instead of smooth rods, lead screws will be used for movement because this removes the necessity of belts that can slip. Hot air is blown into the enclosure to manage the ambient temperature. 3 cameras on different sides of the extruder are used to make a 3d image of the top layer of the prints, this way the process will be monitored and any mistakes during the process identified. The printing surface is a sheet of foil on top of the heat bed. The foil is wound on 2 sides, so the print automatically releases when the foil is rolled up.

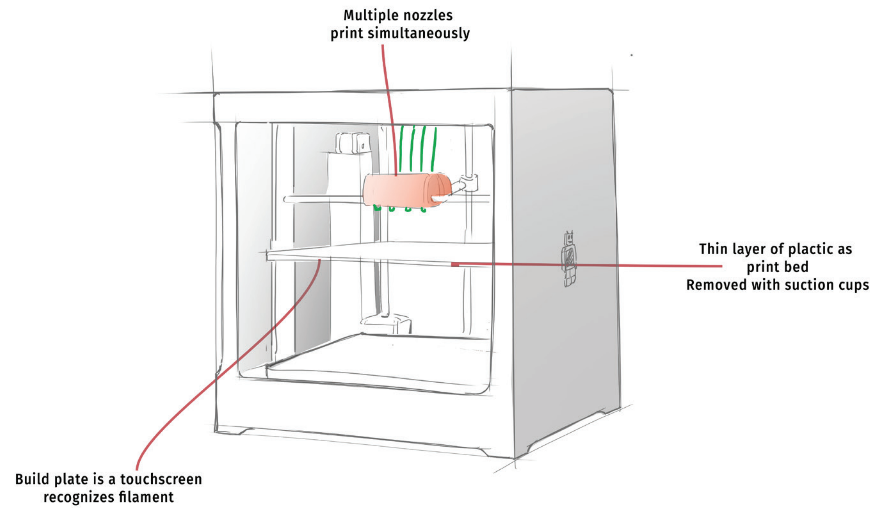


Figure 3.13 Single printer ideation #7

Multiple nozzles print simultaneously to increase productivity and throughput. The build plate is a touchscreen which recognizes filament and can therefor monitor the first layer to see if it is placed correctly. A thin layer of plastic on top protects the touchscreen and can be removed for easy removal of prints.

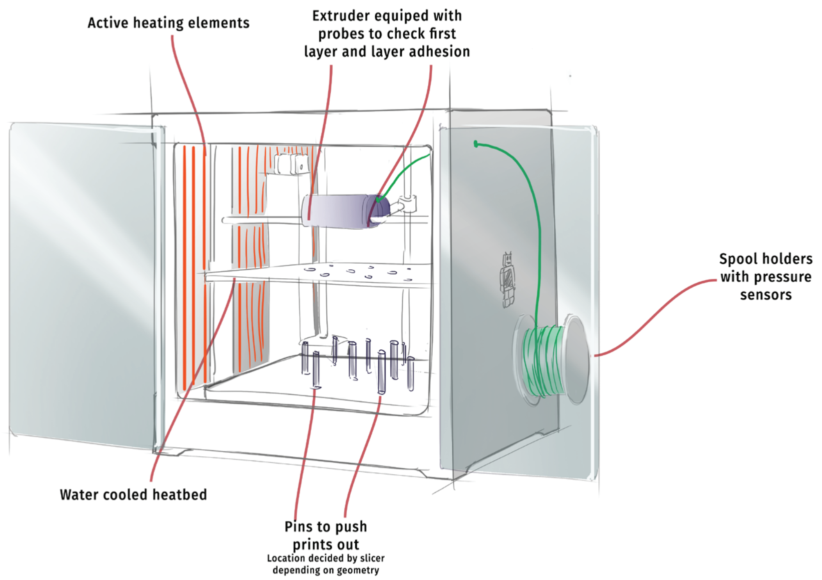


Figure 3.14 Single printer ideation #8

Printer #8 has some features that can be found in injection molding. The build plate is water cooled after prints are finished for easier removal, pins underneath the build plate are used to push the print for the printbed. The spool holder has an embedded pressure sensor to measure the amount of material printed and sends a signal if the spool is almost empty, so that it can be replaced in time. The extruder contains a probe that is used to check the layer adhesion, by pushing against the last layer printed. Active heating elements control the ambient temperature for optimal printing parameters.

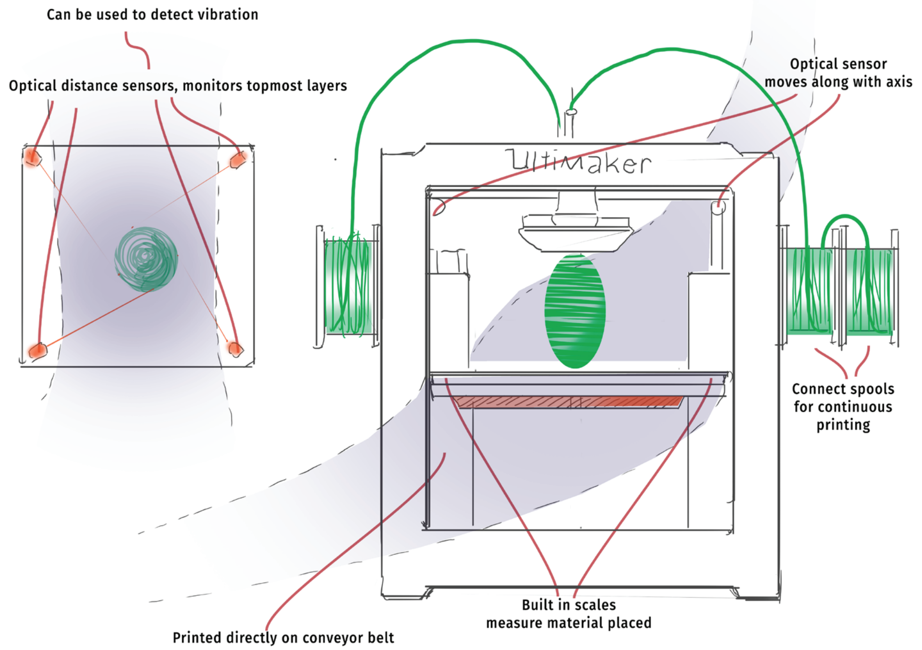


Figure 3.15 Single printer ideation #9

Printer #9 prints directly on a conveyor belt that moves through the printer. This way there is no need for replacing print beds as the belt can be moved to make a new part of printbed available after a print is finished, increasing productivity. The corners of the build plate have built in scales, to measure the amount of material placed and the location to increase reliability. Spools can be connected so printing continues after a spool runs out of filament. Optical distance sensors are placed in each of the corners of the printer and move along with the axes to monitor the printing of the top layer and detect any unwanted vibrations.

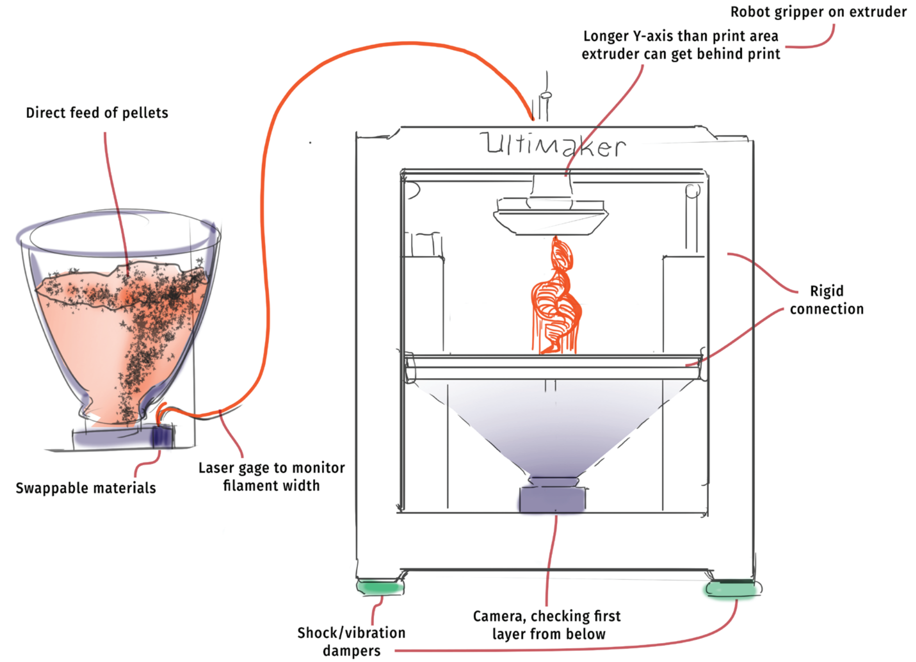


Figure 3.16 Single printer ideation #10

A string of filament is created from pellets and directly extruded to the printer for the same reasons as mentioned in printer #4, this solution however, removes the added weight from the extruder. The extruded (by the filament machine) filament is monitored with a laser gage, to verify the quality of the filament diameter. The material can be changed to maintain the versatility of FDM-printing. A camera monitors the first layer from below the print surface. The extruder body contains a gripper and is able to push the print of the printbed after the print is finished.

3.4.3 Ideas (combining and grading)

The ideas were rated on their levels of improving up-time, accuracy, adaptability and price as these factors will have influence whether the products will be used. The tool used for the ratings can be seen in figure 3.17. The filled in sheet for each of the 10 ideas can be found in appendix R.

Ideating further, combining the high graded ideas and working towards a bigger scale of production level gave the first ideas towards automated print farms with some smartness features as illustrated in figure 3.18.

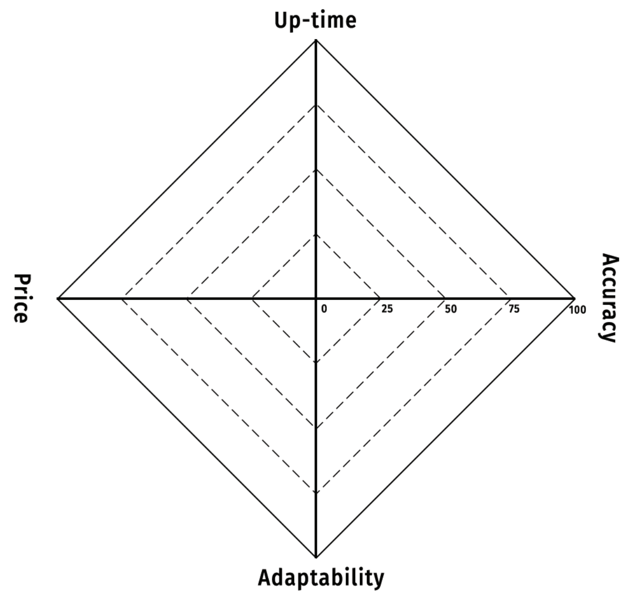


Figure 3.17 Grading tool

Looking at the printers in this scale unveiled some new problems, as cooperation between the machines becomes more important for success. It will become harder to keep track of all the processes, so automation will become more of a necessity in the various tasks (identified in 3.4.1).

The three ideas listed in 3.18 are the Ultitower, Ultiroller and Ultiselector. Each is a combination of the ideas presented in 3.4.2 and aims to give a complete solution for FDM printing in the industry.

The Ultitower is a tower consisting of 4 printers. It is scalable in a way that more towers can be placed next to each other. The build plates are self-ejecting and are ejected on a conveyor belt in front of the printers, which moves up and down between the machines. New build plates are then loaded from behind. The printers have a shared heating system for optimal printing conditions and shared tool heads, to swap between different nozzle sizes between products. A single device is used to monitor the processes run. Each tower has one compartment for filament at the bottom, which has a capacity of 24 spools, meaning each printer has 6 allocated slots.

The Ultiroller is optimized for the use of printing on foil. The system is scalable by placing more printers behind each other. A product is printed on foil and released to a gripper in the center, which in turn places it somewhere where it can be collected. The system is scalable by adding more printers to the side.

The Ultiselector is comparable to an automated parking garage. The printers are placed in a circle. A rotatable elevator moves between printers to collect and deliver build plates. The printers are accessible from the outside for easy maintenance. Spools are on the sides of the printers. The selector is fully enclosed for optimal printing conditions.

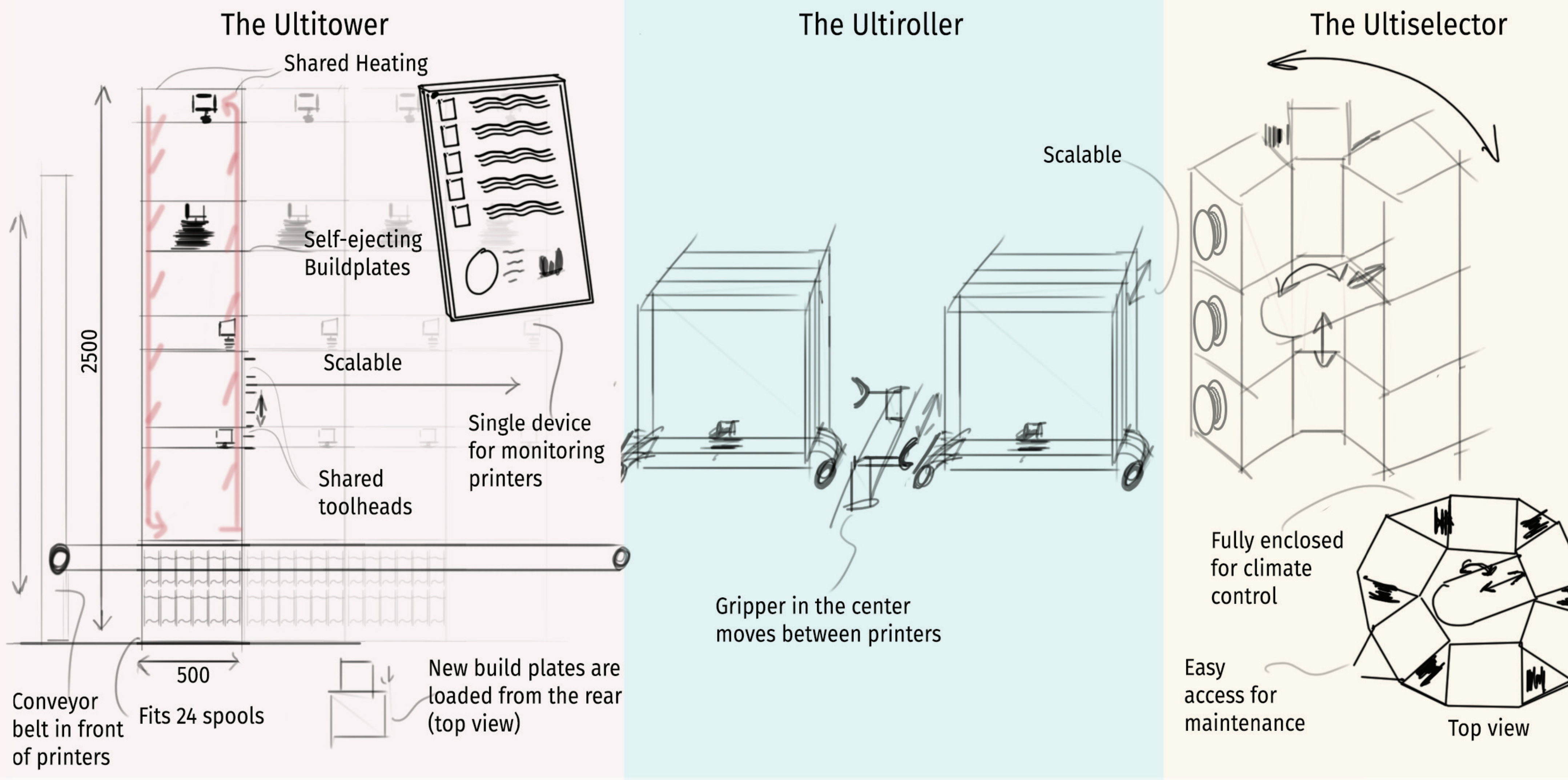


Figure 3.18 Automated print farms

3.5 Initiating conceptualization

The ideas proposed in this chapter have been discussed with experts and analyzed on their added value for FDM printing in industry 4.0 and the list of requirements (2.6.2). The selection will form the foundation of the two concepts that will be proposed in chapter 4. The selection consists of chosen ideas (3.5.1) and insights (3.5.2).

3.5.1 Ideas used in the concepts

The ideas that laid the foundation to the concepts were selected on feasibility and how they would improve FDM printing towards Industry 4.0. Along with the list of requirements and the framework set up for industry 4.0, the ideas were a starting point for inspiration in the development of the concepts.

For the first Concept:

- Multiple spools are inserted, combined when one runs out, possibility to load new spool during printing
- Self-driving printbeds, leaving the printer when printing is done
- Heated air curtains (this later became PVC curtains) to keep heat in printing area while having a flexible way of going in/out of printer
- Oven to preheat new print beds
- Active heating element inside the printer
- Modular extrusion head
- Printers paired, printbed rolls out of the printers
- Material fed from below the printers
- Single device for monitoring multiple printers
- New printbed loaded after print is finished

For the second Concept:

- Heavy spools, to decrease the amount of switching of spools
- Heated air curtain, to keep heat in printing area while having a flexible way of going in/out of printer
- Layer of foil on top of heat bed, wound on 2 sides so print falls off when rolled up
- Printed directly on conveyor belt, to move through the factory
- Scalable system where printer prints directly on belt between printers
- New built plates are loaded from the rear
- Conveyor belt in front of the printers, transports ejected printbeds

3.5.2 Insights used in the concepts

The Insights found that were used as a foundation for the concepts are listed below.

For the first Concept:

- Carriages enable Industry 4.0 production lines
  - Festo Concepts
  - Bosch Concepts
  - Phoenix Contact Concepts
- The climate in which a print is done is extremely important for the quality of prints
  - Multiple sources
- A company will rather have 10 bad prints that are exactly the same than 10 different, of which 5 are very good, prints
  - David Braam (Founder of Cura)

For the second Concept:

- When adding electronics or other components you want to have 2 or 3 UM's with a conveyor between them
  - J. M. P. Geraedts

4. CONCEPTUALIZATION

This chapter will discuss the two concepts made after the ideation phase. It will start by introducing the two concepts (4.1), where the way both concepts were founded is discussed as well. Scenarios have been created to test and compare both concepts (4.2) and make a well-founded choice between the two (4.3). The chosen concept was then worked out further (4.4) and prepared for the embodiment phase (Chapter 5).

4.1 Two concepts

Both concepts were developed as a combination of various ideation steps and insights, while targeting to remove/decrease human interaction with the system.

The initial ideas for Concepts 1 and 2 are illustrated in figures 4.1 and 4.2 respectively, with a global description of their features.

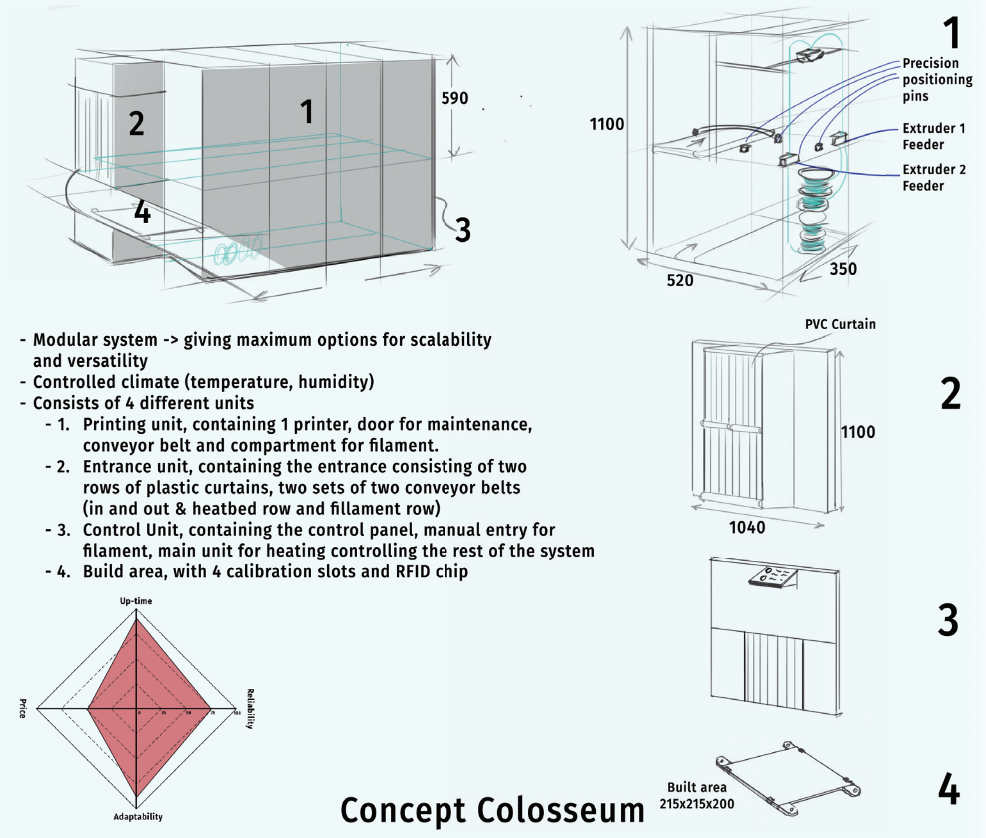


Figure 4.1 Concept 1

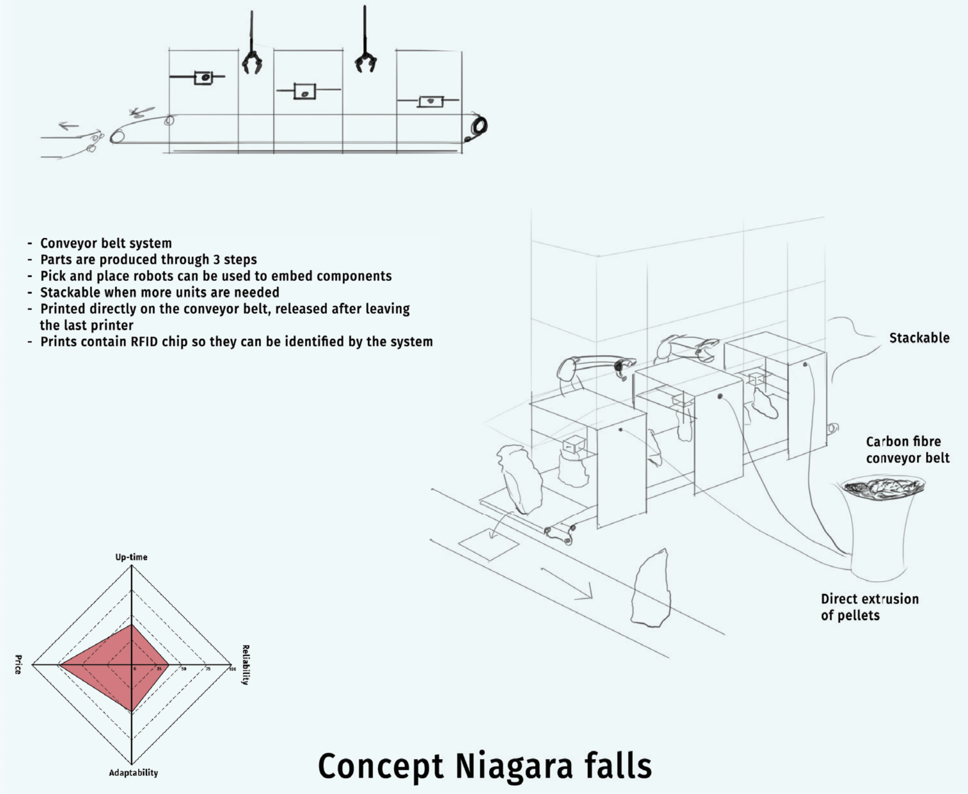


Figure 4.2 Concept 2

4.2 Concept scenarios

To get a better idea of the capabilities of the concepts (where the further developed is explained in 4.2.1), 3 products that will be 3D printed have been selected (4.2.2). These will go through a theoretical production line and comparisons will be made between the total timespan, down-time of the printers and the flexibility of the system (4.3). For both concepts the workflow is discussed in chapter 4.2.3.

4.2.1 Concepts explained for the scenarios

Concept 1 (figures 4.3 & 4.4) features a modular printing hub that is connected to the smart factory line. Printbeds enter the hub on carriages and the system selects an available printer for that printbed. Material is loaded underneath the printer, where multiple feeders are present, if a spool is empty another feeder is selected, so there is minimum downtime when a material runs out.

Concept 2 (figure 4.5) features a conveyor belt directly under the printer. Next to the printer is an assembly station. Prints are printed directly on the conveyor belt. When they are at a predefined point and need embedded parts, the belt moves the print out of the printer to the assembly station. When assembly is done the print returns to the printer and resumes.

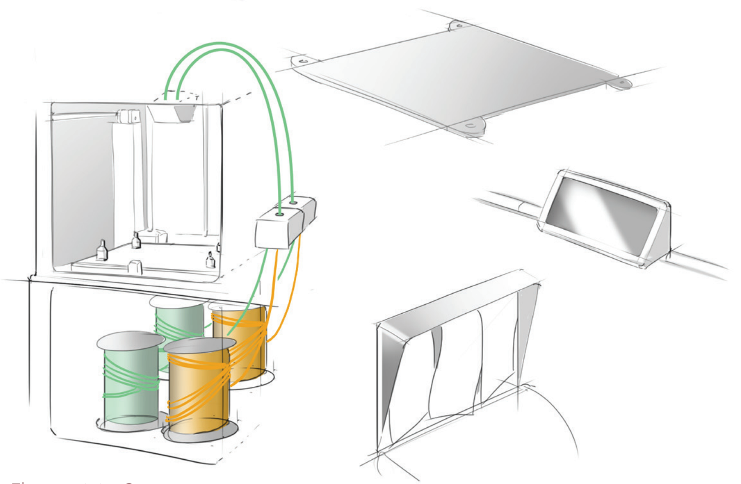
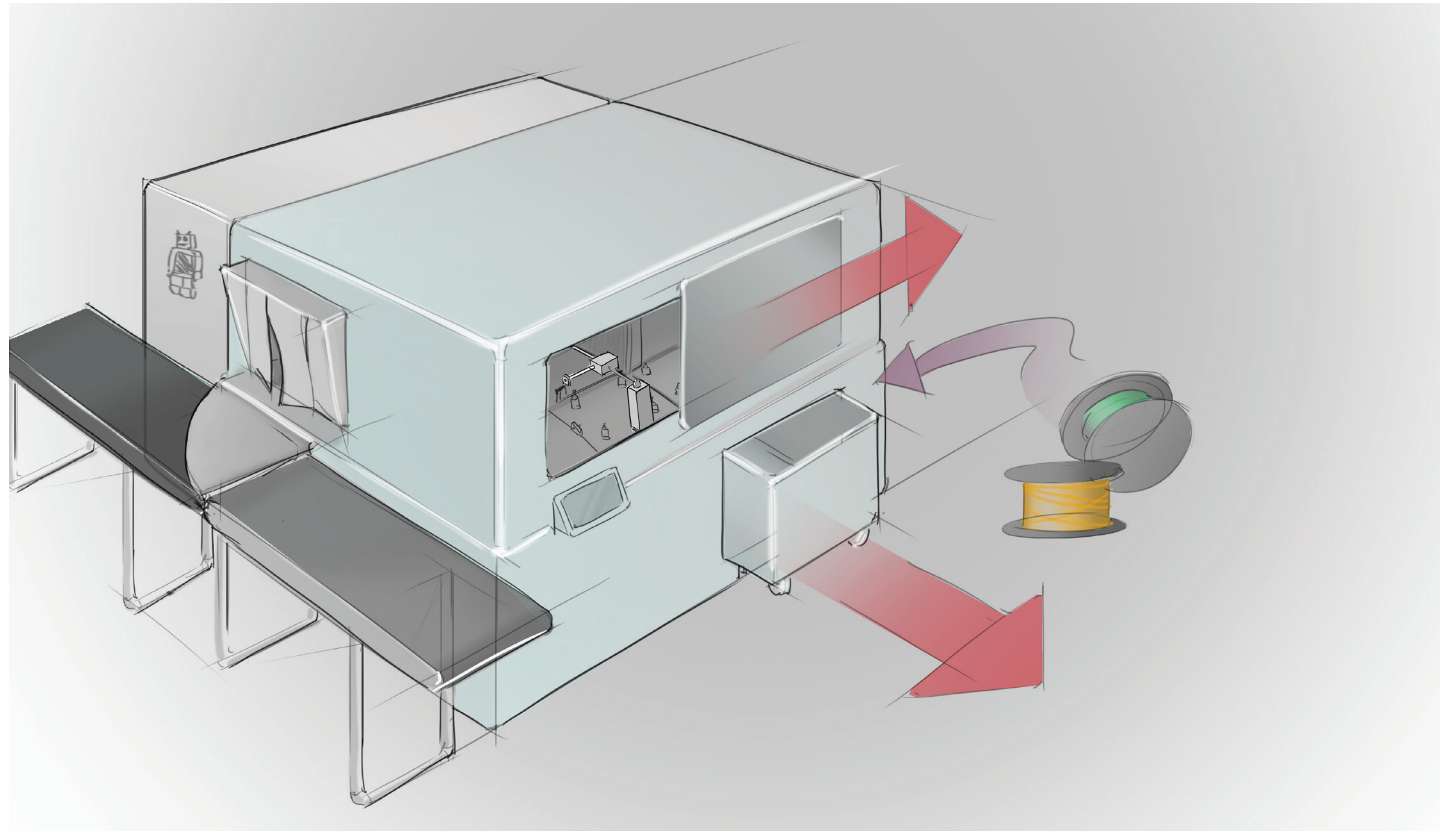


Figure 4.4 Concept 1 components

Figure 4.3 Concept 1



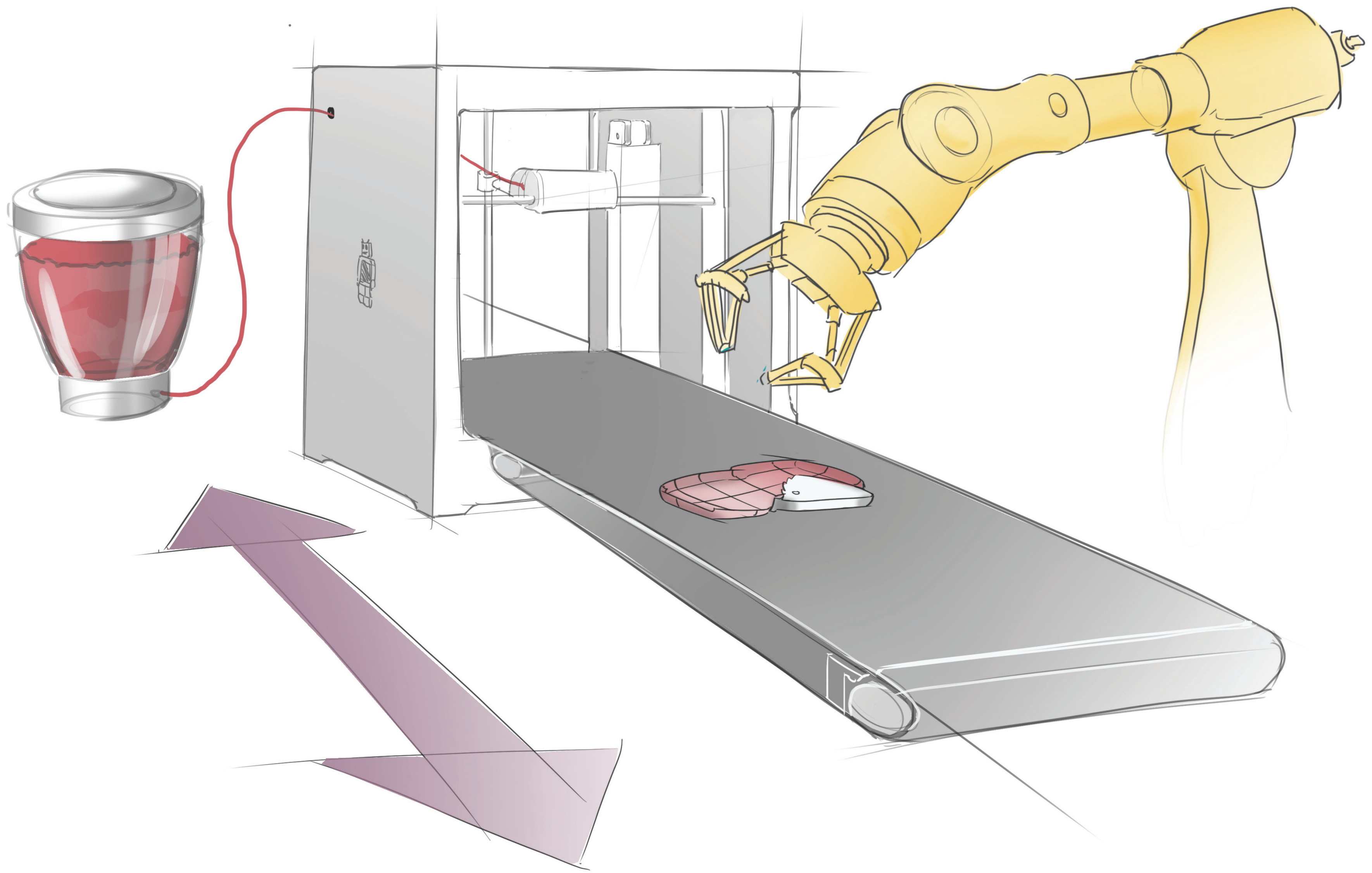


Figure 4.5 Concept 2

4.2.2 Products

Three products have been selected to demonstrate the use and functionality of the concepts. The aim is to use these products to find strengths and weaknesses for the concepts and eventually assist in choosing which the final concept. The products have been selected as they vary in the way they are produced and steps in that production process.

4.2.2.1 Dynamo lamp

The Dynamo lamp, a product which students work on in the subject PO4 (faculty of IDE at the TU-Delft). During that project, students have to redesign and 3D print a hand driven dynamo lamp. Hand driven products are important tools for places where there is no electricity available. The Dynamo's are mainly printed but have embedded components that are added in the process. Figure 4.6 illustrates a 3D printed dynamo.

4.2.2.2 Exo-L Brace

The Exo-L brace is designed to act as a safety belt to protect when the wearer is about to sprain their ankle (Exo-L, 2019). It is 3D printed after a scan of the ankle has been made, meaning each product is different. The Exo-L has an embedded strap which is connected to the users' shoes. The Exo-L can be seen in figure 4.7.

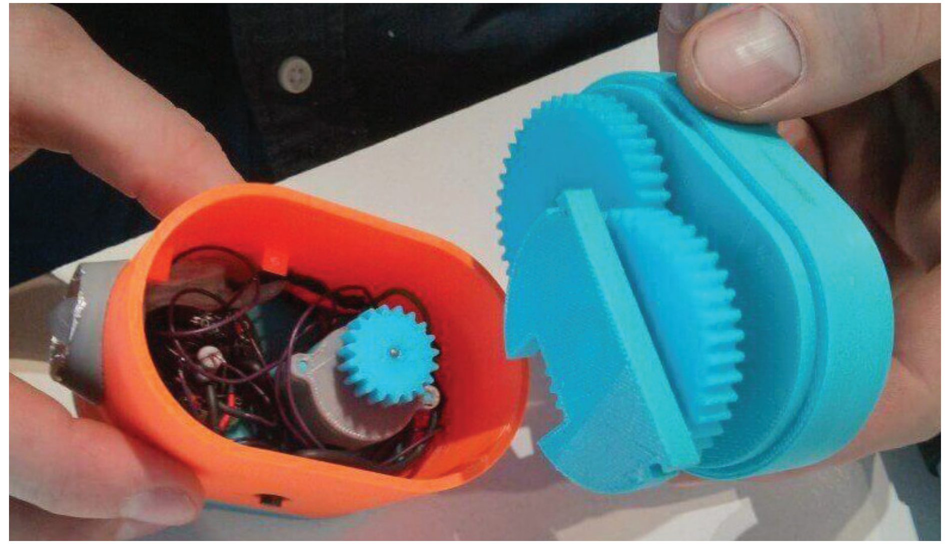


Figure 4.6 3D printed dynamo lamp (All3DP, 2016)

Figure 4.7 Exo-L

4.2.2.3 I-SEE (Glasses)

The aim of the I-SEE project is to develop and launch a new eyewear product line and a platform of services focused on improving the health care and wellbeing of eyeglasses wearers (I-See, 2019). Its intent is to monitor the viewing and living experience of the consumers and allowing eyeglasses to interact with smartphones, in-car telematics and professional devices of practitioners and opticians.

The I-See products will be equipped with state-of-the-art electronics components and sensors. These will collect and transmit information to consumers' mobile apps as well as to professional solutions of eyecare specialists. The I-See project has been chosen as their only solution to produce the glasses with all of the embedded components has been 3D printing. Figure 4.8 illustrates a prototype of the I-see glasses and its embedded features.

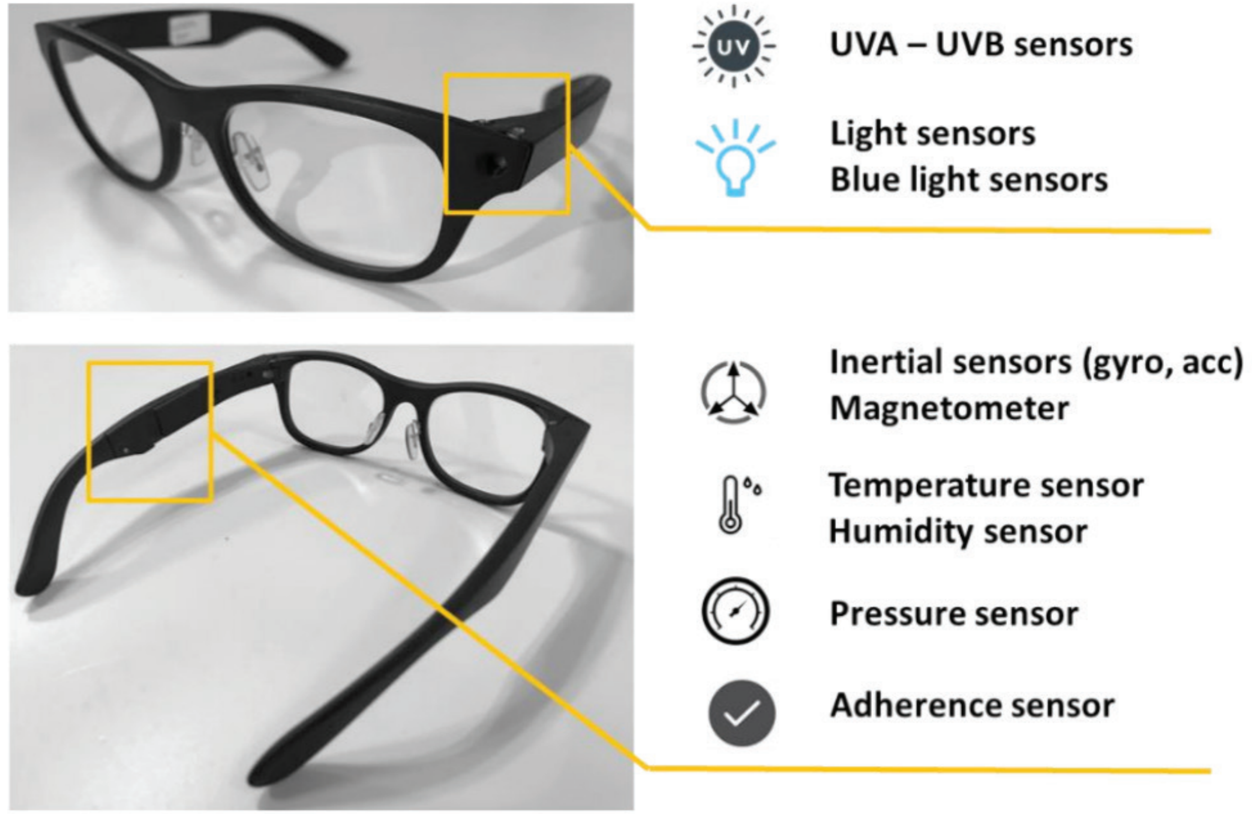


Figure 4.8 I-SEE glasses (Cordis. Europe. 2018)

4.2.3 Workflow

This chapter will relate the concepts to the workflow proposed in chapter 2.5. Figure 4.9 shows the workflow for concept 1, with the area in which the concept will operate marked in red. Figure 4.10 shows the same for concept 2. For both concepts the workflow will be listed afterwards. The main differences are found in the way products are processed in the area marked in red.

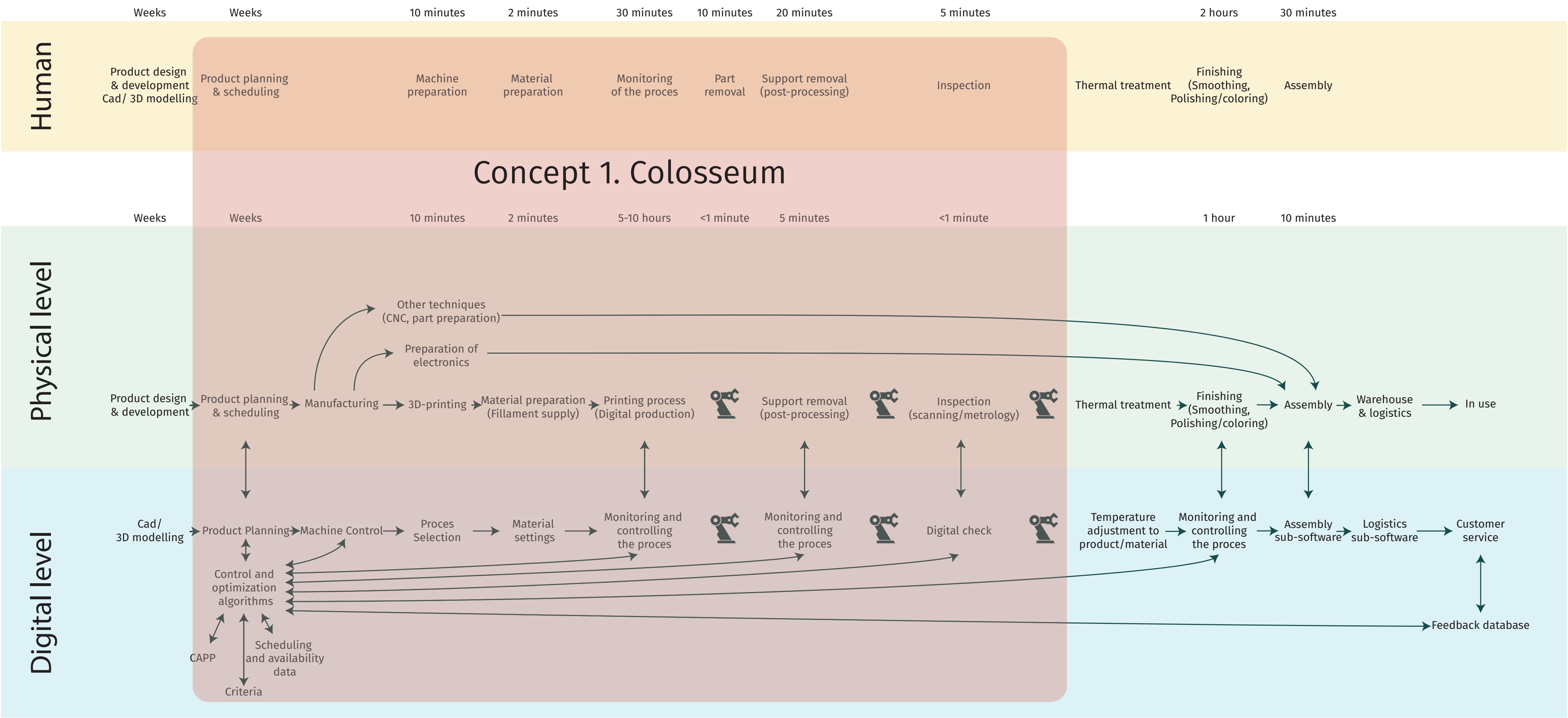


Figure 4.9 Workflow concept 1

The entire workflow of a product within concept 1 will be described below to identify all the factors of influence.

- There is an idea for a product
  - This idea is modelled in CAD
    - Tolerances
    - Material properties
    - Simulation
      - Process simulation
      - FEA
    - Feedback to this model during the process
  - Gcode generation
  - Overall more integration in software and less conversions, meaning less loss of data, increasing accuracy and precision
- Product planning & scheduling
  - Available machines are read in the system, a schedule is made digitally
  - A planning for when steps are taken, how they are taken and when is made
  - Planning what material will be used
  - Planning when production is done
  - Carriage made available; RFID tag connected to necessary information
- Material preparation
  - Material is ready and fed before printing starts
  - Feeding happens from below the printer
  - Material is placed inside (re-usably) crates that contain RFID tag connected to data about the material
  - Crates connect to feeding system
  - Optimized environment inside crates is maintained to ensure material quality
  - Amount of material left on spools is tracked
  - System is notified when there is an empty feeding slot, new material dispatched
  - When a spool is empty the next is ready to be fed to the extruder
  - When a spool is empty the crate is returned to storage for refill
- Printing process
  - Printbed prepared (process dependent of material)
  - Calibration before print starts
    - Calibration data stored and connected to RFID tag
  - Done in optimized environment
  - Heating element for controlled temperature
  - Curtains to keep heat in (while it's easy to enter and depart)
  - Ability to remove printbed, add parts, return printbed and continue print
  - Scanning, assembly, preheating and removal happen outside printer
  - Use of internal sensors
    - Store data of sensors, relate those to the print
    - Compare scan to CAD data
      - Record sensor data and compare with scan results
  - Easy access for maintenance (Appendix M)
  - System is modular and scalable
  - Adjusts to production line
- Product leaves printing station
  - Passes scanning station, data collection
  - Product is recognized by RFID tag, system knows following steps
  - Passes necessary assembly stations
  - Passes processing stations
  - Return to printer (if available and applicable)
  - To release station when needed
- Release from printbed
  - Depends on material how this will happen, printbed material as well
  - RFID data is transferred to next carrier

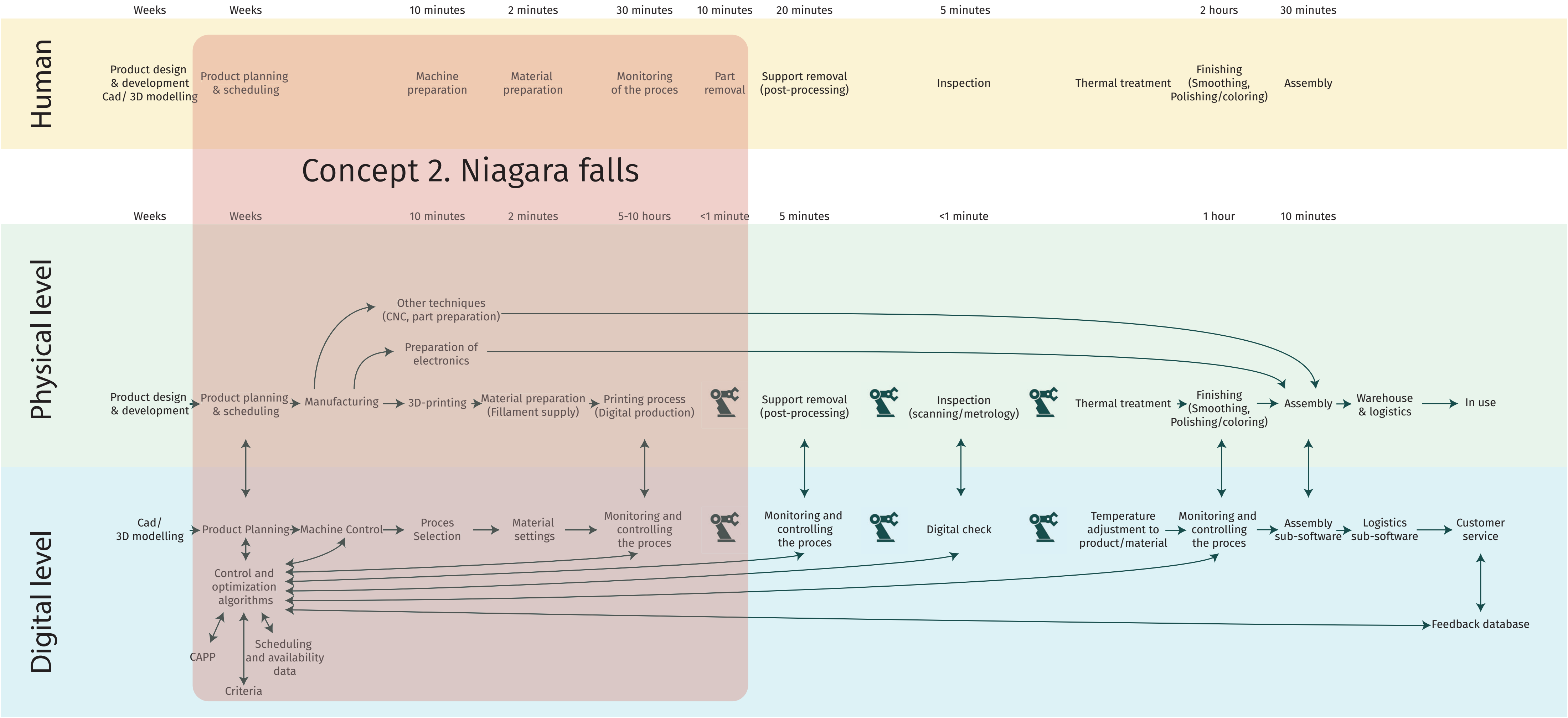


Figure 4.10 Workflow concept 2

The entire workflow of a product within concept 2 will be described below.

- There is an idea for a product
  - This idea is modelled in CAD
    - Tolerances
    - Material properties
    - Simulation
      - Process simulation
      - FEA
    - Feedback to this model during the process
  - Gcode generation
  - Overall more integration in software and less conversions, meaning less loss of data, increasing accuracy and precision
- Product planning & scheduling
  - Available machines are read in the system, a schedule is made digitally
  - A planning for when steps are taken, how they are taken and when is made
  - Planning what material will be used
  - Planning when production is done
  - RFID tag is prepared, placed in pick and place station next to the printer, embedded inside print during the process
- Material preparation
  - Material is ready and fed before printing starts
  - Number of pellets left is measured, refilled if necessary
  - Feeding happens from the side of the printer
  - Filament is created from a compartment filled with pellets
  - Quality of filament extrusion is monitored and data is stored
- Printing process
  - Conveyor belt surface prepared for print
  - Calibration before printing starts
    - Calibration data stored and connected to RFID tag
  - Ability to move print out of printer, add parts, return printbed and continue printing
  - Use of internal sensors
    - Store data of sensors, relate those to the print
    - Compare scan to CAD data
      - Record sensor data and compare with scan results
  - Easy access for maintenance (Appendix M)
  - System can be scaled by adding more printers and conveyors
- Released from conveyor belt
  - The belt rolls up on one side, print falls of the belt and continues through the factory, recognized by embedded RFID tag
- Product leaves print station
  - Moves to the rest of the factory
  - Passes scanning station, data collection
  - Product is recognized by RFID tag, system knows following steps
  - Passes processing stations

4.3 Choice of concept

The products discussed in chapter 4.2.2 were used in the choice of concept. Their production method and printing times were estimated and then put in separate timelines (4.3.1). This helped visualize the difference in production times for both concepts and the way they produce parts as well as identifying both strengths and weaknesses. A list of wishes is proposed in chapter 4.3.2. The list of wishes is processed for both concepts to give an objective comparison and help in deciding with which concept to continue (4.3.3).

4.3.1 Timing sheets for concept choice

For the timing sheets it was assumed that both concepts were deployed with 6 printers. The goal was to produce 200 dynamo lamps, 200 Exo-L braces and 100 I-See glasses within a week.

The print time was estimated with Cura, by selecting the material CPE+ (PETG, Appendix B. Materials) and a corresponding profile. Figure 4.11 shows the example of the glasses. The rest of the times were calculated and validated by experts (Appendix E).

The time for each step in the process was calculated and resulted in the timing sheets found in Appendix S. Two example of one of those sheets can be found in figure 4.12 (Hand dynamo in concept 1) and figure 4.13 (Hand dynamo in concept 2).

The sheets visualize the time calculated for production from the moment a print is initiated to when it is finished. Red marks the first batch of products and blue the second batch. The colors indicate what happens at which moment in time and how long that takes.

For all the products combined it took concept 1 a total of 130 hours and concept 2 took 145 hours. Both managed the production within a week (as the concepts can both operate 24/7). However, concept 2 was more than 11% slower. This can be derived from the fact that downtime is minimized in concept 1. This difference will become even higher when a printer will have different products (which is one of the main strengths of FDM printing), as the entire assembly setup will have to be adjusted. For these sheets it was assumed there were no errors in the proces (which in reality does happen).

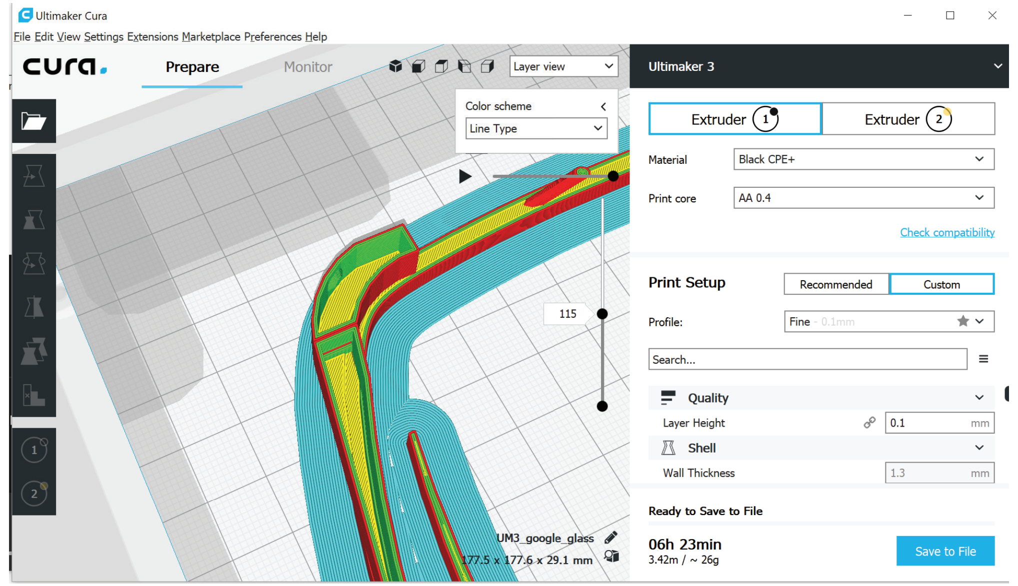


Figure 4.11 Glasses in Cura

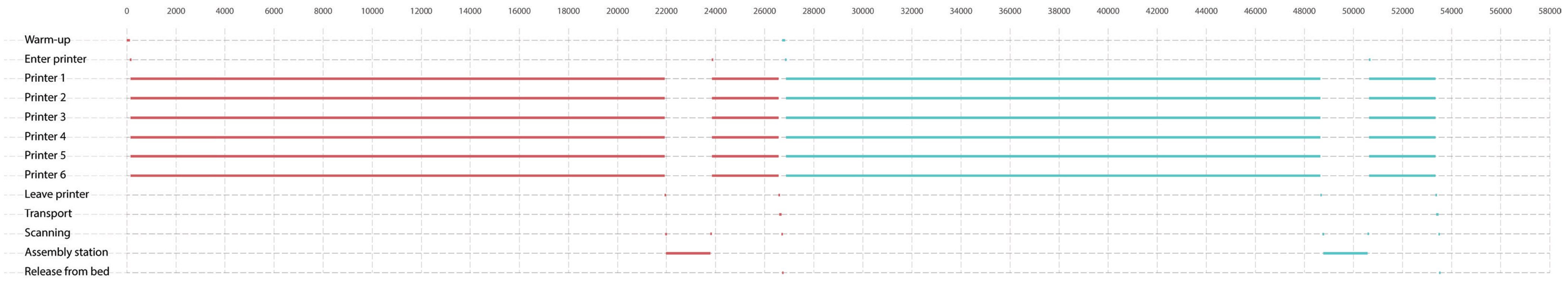


Figure 4.12 Timing sheet concept 1, Hand dynamo

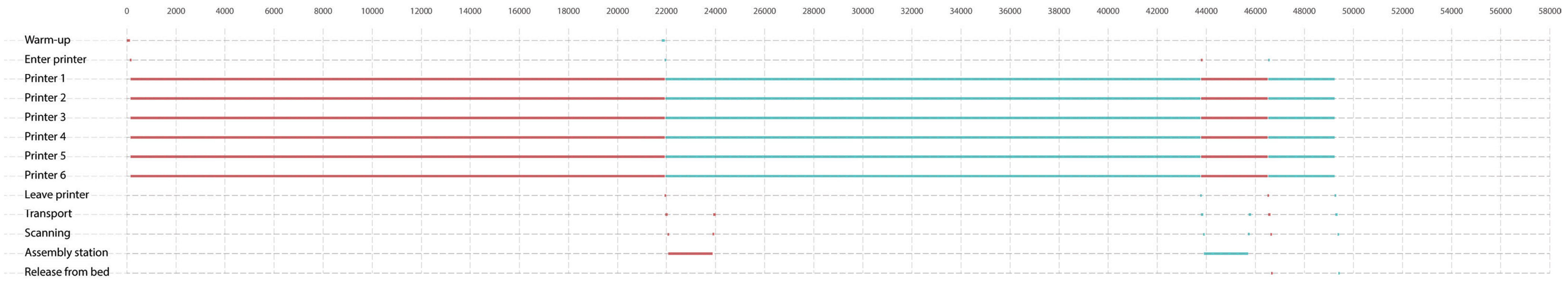


Figure 4.13 Timing sheet concept 2, Hand dynamo

4.3.2 Wishes

Table 4.1 lists wishes for both the concepts, these wishes follow from the analysis (chapter 2) and were then rewritten during brainstorming in chapter 3.4. In that phase of the project the design drivers (chapter 2.6.1) were used as a starting point for the wishes.

Wishes	Concept 1	Concept 2
Ability to add new/have multiple different product in the production line	Yes	No, needs adjusting at the line
Scan during the process	Only when print leaves the printer	Only when the print leaves the printer
Freedom of adjusting the process	Yes, with the limitations of the carriages	Little, as each of the printers has its own assembly station
Integrated release of the print	No, separate station is needed	Yes
Variety in materials	Yes	If it is printable on carbon (material of the belt)
Down-time	About 30 seconds (between printbed swaps)	Duration of the assembly
Printing in optimized environment (with controlled parameters)	Yes	No

Table 4.1 List of wishes

4.4 Chosen concept

Concept 1 was chosen and will be the base of the embodiment phase. This chapter will give more information on the chosen concept, now named the UltiFact 4.0, along with an exemplary production line for a industry 4.0 factory.

UltiFact 4.0

Figure 4.14 illustrates a map of the UltiFact within an Industry 4.0 production line. The Ultifact will function as a printing hub connected to the rest of the line. Carriages travel throughout the line. If a printer is free (and a printed part is needed) the carriages enter the printing hub. After printing the carriages leave the hub and are transported to the next hub needed for production.

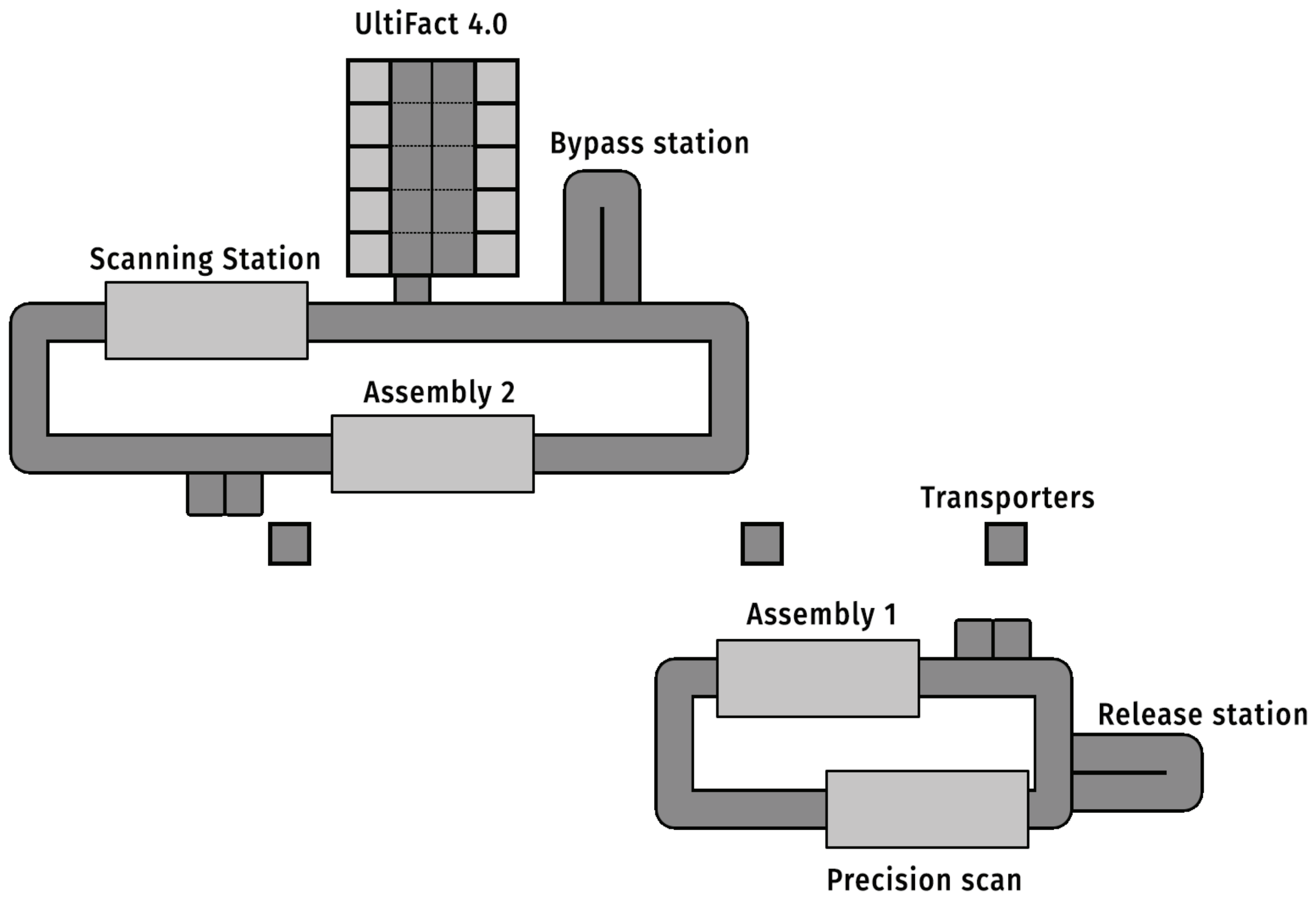


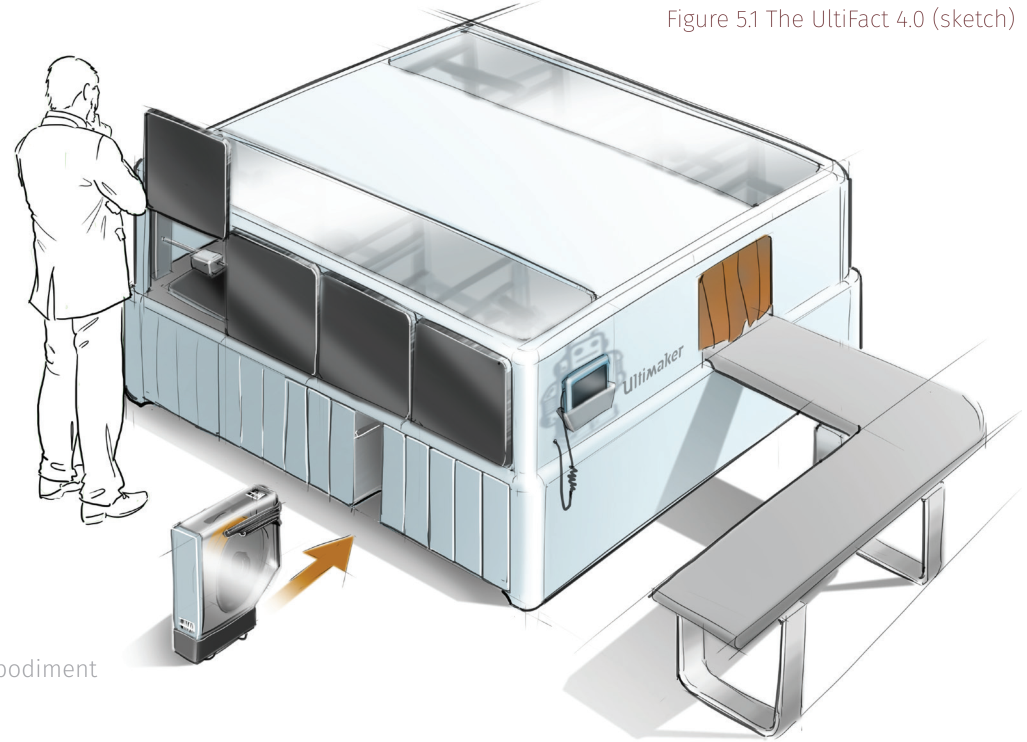
Figure 4.14 The Ultifact 4.0 example production line

5. EMBODIMENT

Chapter 5 reports on the final phase of the project, the embodiment phase. Steps taken to get from the proposed concept in chapter 4 to a final (concept) design will be discussed.

The chapter starts by highlighting the features of the UltiFact 4.0 (the design before the iterations in this chapter can be seen in figure 5.1) in chapter 5.1 along with sketches of the concept. Chapter 5.2 will report on the prototyping done during to prove selected features. This will lead to a redesign in chapter 5.3 where more detailed features will be presented with renders and how these features came to existence. The list of requirements (2.6.2) is discussed and an evalution is made on how the concept complies to the list in chapter 5.4.

Figure 5.1 The UltiFact 4.0 (sketch)



5.1 Features

This chapter will list the features of the UltiFact. Figure 5.2 shows a sketch with the key features numbered which will be discussed briefly below.

5.1.1 Ultifact 4.0

1. Shared enclosure

The printing units are connected and stand in a shared enclosing unit. The heating is shared among the printers to keep a stable environment. Each unit does have its own PID controller and heating units because the heated bed and the extruder can influence the ambient temperature in the units.

2. Maintenance hatch

Maintenance has to be done, and problems do occur during prints. Therefor it is important an operator is able to access the printing units.

3 Curtain at the front

A curtain has been placed at the entrance of the UltiFact 4.0. It is necessary to close off the opening to control the printing parameters. It is important to have a stable ambience temperature while printing (chapter 2.2 and experts) each material has its own ideal ambience temperature, any fluctuation in ambience temperature can cause anomalies in prints (like warping or bad layer adhesion).

A curtain has been chosen as it takes up less space than a swinging door (which is especially important inside the printers. The material is easy for carriers to pass through passively, so there is no need for an additional mechanism. Research and the folowing iteration step on the curtains will be discussed in chapter 5.2.1.

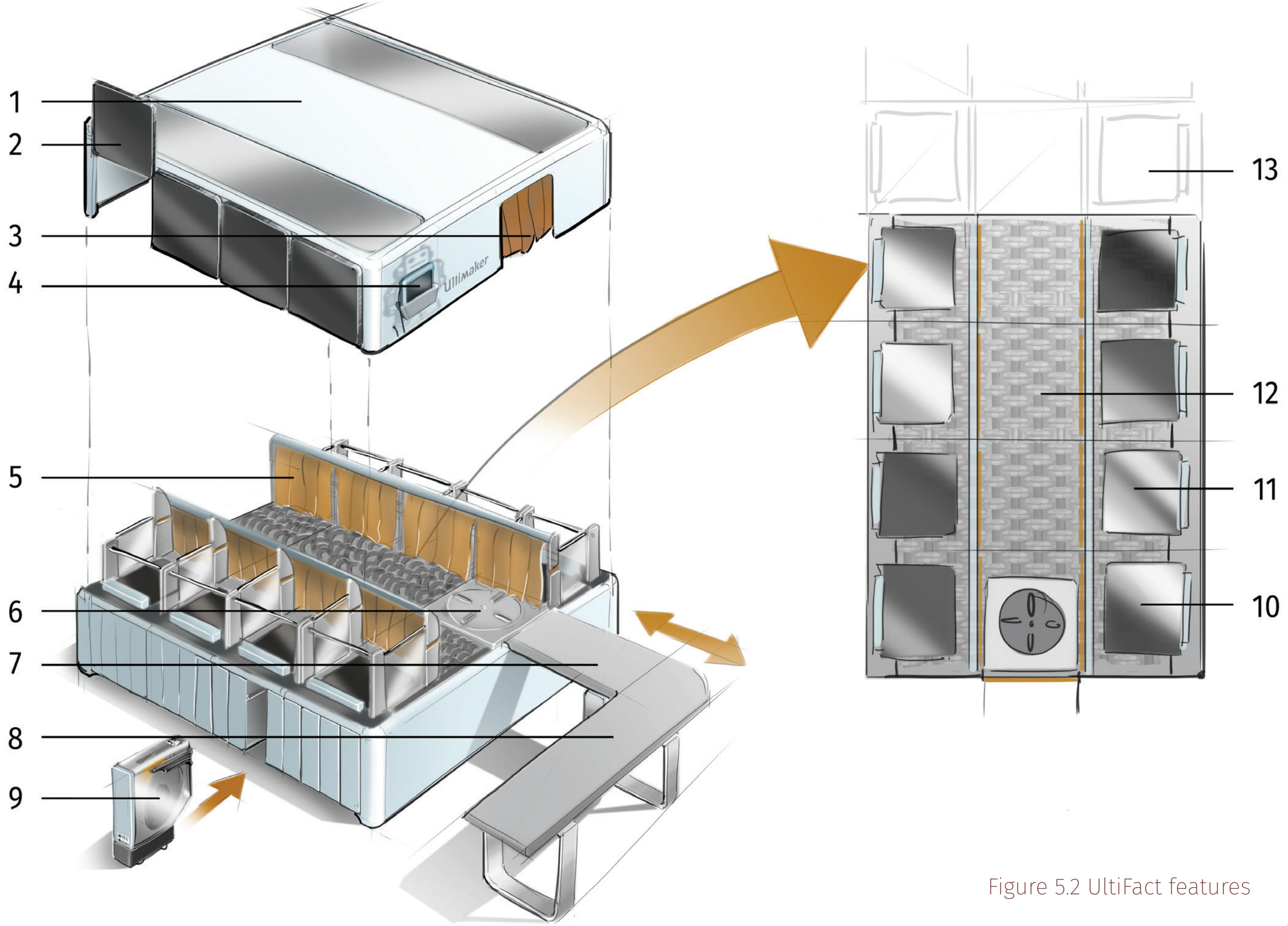


Figure 5.2 UltiFact features

4. Single screen

All printers are connected, meaning all printer information is available at a central hub (connectedness, one of the Industry 4.0 requirements, chapter 2.3). Production is directed from this location. In case of maintenance, issues or hand-on monitoring, the tablet attached to the printer is used (figure 5.3 shows some examples of the use of this tablet). The tablet interface assists the operator (human machine interaction) in the process.

5. Second layer of curtains

Each printer has an extra curtain in front to make sure no fluctuations in temperature can happen. This is necessary as there are printbeds moving through the center space that can affect temperatures. The same goes for other printer units that can affect the temperature. This part will be developed further in chapter 5.2.1 (curtain research).

Figure 5.3 Tablet interface

6. Rotatable platform at the entrance

The carriers that enter the printer (number 10) are equipped with a kinematic coupling. This coupling only works in one direction, meaning the carriers have to be placed in the correct orientation. For this to happen a rotating platform is placed at the entrance. This will rotate the carrier in the needed orientation before entering and when leaving the UltiFact.

7. Conveyor belt in front of the entrance

The conveyor that is placed in front of the Ultifact works in two directions. This is a step further than the first version of the concept where one conveyor was used to enter the chambre and another to leave it. It was chosen to use a single conveyor for this because it minimizes the opening needed and this path will only be used when prints are done or started, which means that a single conveyor has enough capacity.

8. Adjustable to production lines

Can be adjusted to fit in any production line that is capable of processing carriers.

9. Material in boxes (image)

Material is placed in climate-controlled boxes (figure 5.4).

9.1 Material boxes
Spools are transported in sealed boxes. The air inside is optimal for the material. The boxes are connected to the printer and material is fed directly from the boxes. Each printer has a capacity of four boxes. Two times main material for extruder 1 and 2 times the support material for feeder 2. Once a spool runs out of material the other spool takes over and the empty box is replaced, to maximize up-time.

9.2 RFID chip
The boxes are equipped with RFID chips, this way the factory system can read which material is inside and track the data. The amount of material printed is tracked with this chip and as soon as the filament runs out it is replaced.

9.3 Material robot
An autonomous robot is used to bring the boxes from the magazine to the necessary material slot. When a spool runs out of material the robot drives underneath the box, removes it from the printing unit and replaces it with a new one.

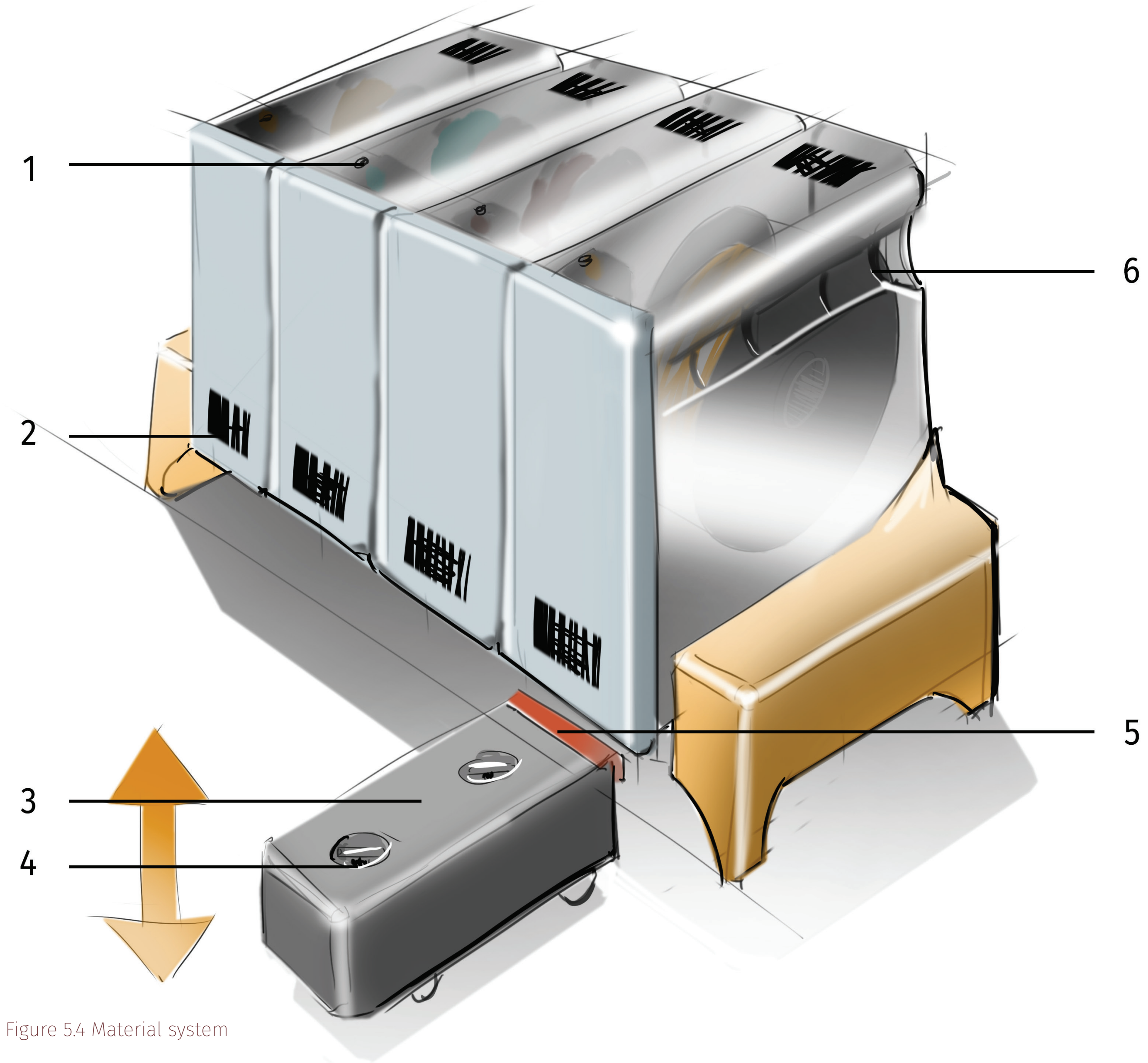


Figure 5.4 Material system

9.4 Locking mechanism
The robot has a locking mechanism that can be raised. When it is underneath a material box it raises the mechanism and locks itself to the box. This way it won't fall off while moving. The mechanism unlocks once the box is at the desired location.
9.5 RFID reader
An RFID reader in the robot scans the material boxes to verify whether the right box is selected.
9.6 Guided rail system
A guided rail system is embedded in the material boxes. The boxes hang in the printer units and align the material precisely with the material feeder of the printers.

11. Carrier system (image)

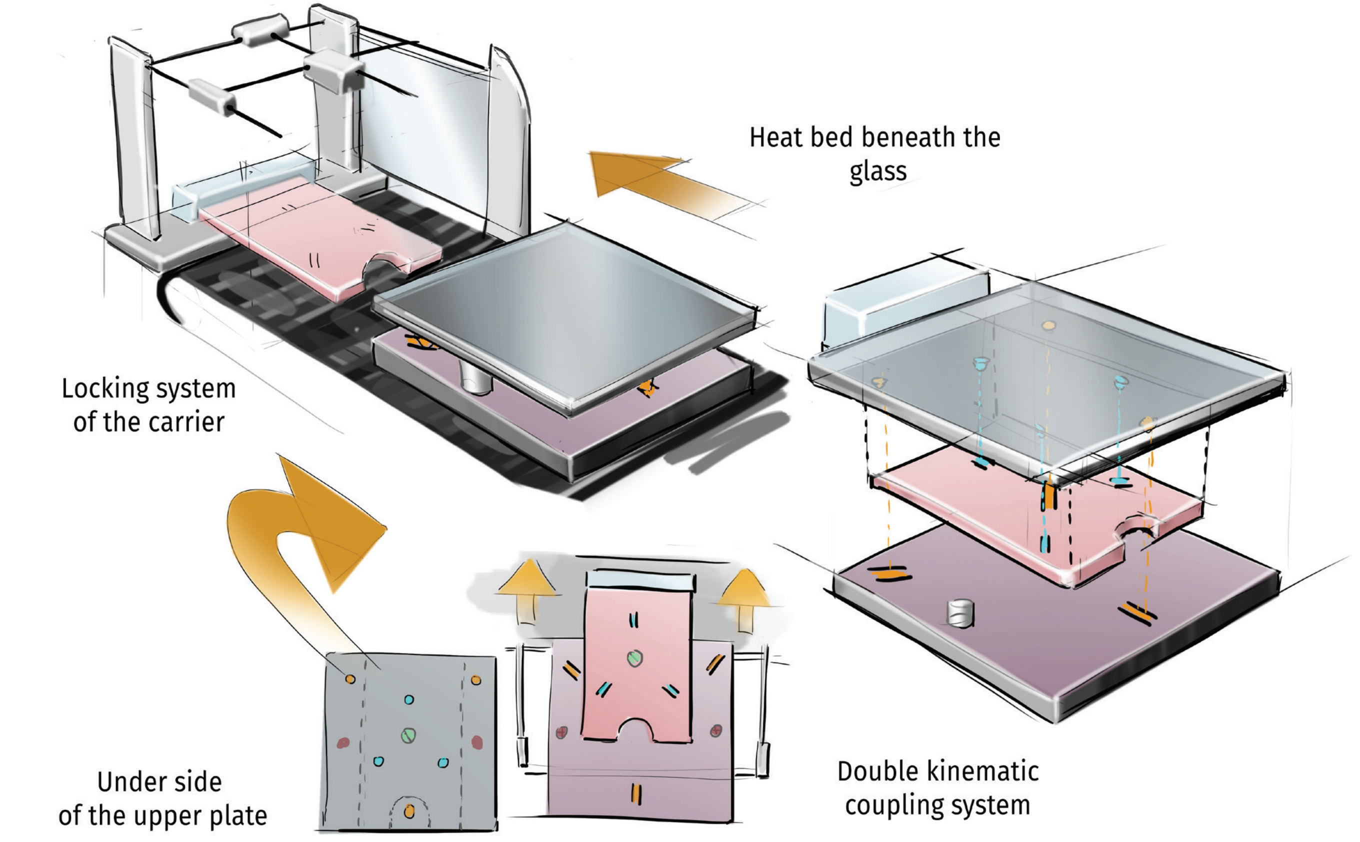


Figure 5.5 Carrier system

Figure 5.5 illustrates the carrier system, featuring a double kinematic coupling. Further ideation and research on the carrier system will be done in chapter 5.2.2. Kinematic coupling in short are mechanical contacts used to precisely locate components with respect to each other. It uses three contact points to create a plane.

In the measurement and instrumentation fields, kinematic couplings have been used as a method to create precise and repeatable interfaces on a variety of devices, such as optical lenses and probe mounts. Recently, kinematic couplings are increasingly used in industrial environments on equipment such as engine motors and industrial robots (Culpepper, M. 2007).

The carrier enters the printer unit on a conveyor. The printer carrier (the plate that moves up and down in the Ultimaker printer) moves between the build plate of the carrier system and the bottom part that is on the conveyor belt. By lifting the printer plate, the kinematic coupling is connected with the printer and printing is started. After a print is finished the plate is lowered and the parts of the carrier are again connected through kinematic coupling. The plate of the printer is lowered a bit further so it does not make contact with the build plate anymore. The conveyor then moves the carrier out of the printing unit. This interaction between the systems will be prototyped and further developed in chapter 5.2.2.

12 Build size

The Ultimaker 3 has been used for dimensional references. Meaning a build size of 215x215x200. These dimensions were chosen because it was found to be sufficient for most applications and more printers can be combined in less space. Furthermore, less adjustments to product lines are necessary as opposed to bigger build volumes, that require more space.

13. Multi-directional conveyor system

A multi-directional conveyor system has to be developed inside the shared unit. The carriers need to be moved to the right printing unit and then be placed inside that unit. Further development on this system will be described in chapter 5.3.

14. Modular and expandable

The system is fully modular and expandable. The exact principle for this will be explained in chapter 5.3 where the various components will be highlighted with renders as well. Printing units can be added to increase product throughput, and defect units can be replaced instantly to keep up-time as high as possible.

Connectivity

The entire system is connected to the factory. Tasks are sent from a central hub (figure 5.6), where the entire process can be managed and new orders processed. Data on the status of production as well as amount of error and scheduling is shown here. Scheduling for free printers is done autonomously in this area. Predictive maintenance can be done from here. Data on products is send to the printer through the carriage and the printer keeps track of printing parameters, so product errors can be tracked if they are found.

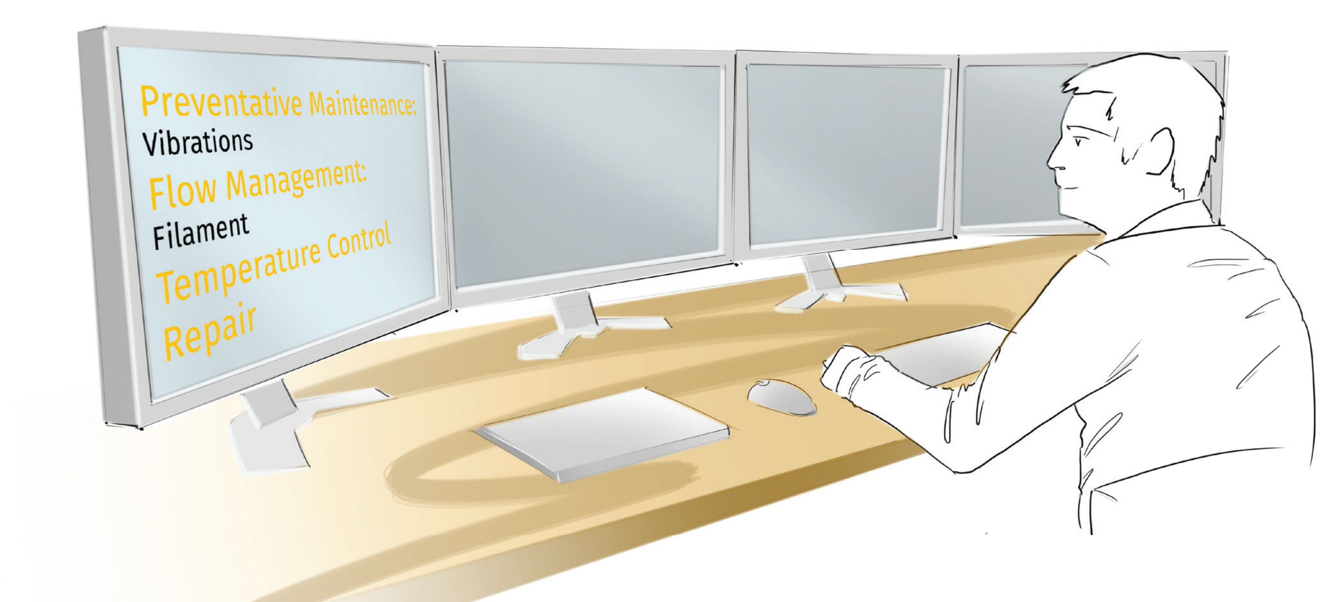


Figure 5.6 Central factory hub

5.1.2 Proof of concept steps

To prove the concept, various steps were identified. This chapter lists the steps that have been taken during the embodiment of the project. It has been categorized in approaching experts, further research, prototyping and designing.

Experts

The input from experts has been processed in the analysis part and the interviews can be found in appendix E.

Industrial Design
- Scanning with camera, how?
  - Keeping track of the process
  - Machine learning/vision (processing power)
- More precise scan (after/between prints)
  - How to match those with CAD model?
  - Tolerances
  - Properties
  - Simulation within CAD model
  - Feedback
- Heating element to control environment inside the printer
- Distance sensor (For use when the print is returned inside the printer)
- Connecting multiple printing stations

Ultimaker
- Which sensors are all available in current Ultimakers, how to use them and what to do with the data?
- Integration of CAD software with Cura
- How does the leveling work, what data becomes available and can this be stored?
- How does the calibration work, what data becomes available and can this be stored?
  - Is this data still relevant after removal and replacement of the printbed?
- Feeding of material
  - Feeder location, feeding from below the printer, how does it exactly work?
- Material crates, what is needed to maintain perfect conditions for material?
- PRINTING PROCESS
  - Printbed preparation for prints, how to have it in optimal condition for printing, what is recommended per material, are there any developments here? Any new materials for printbed?
  - What would be the perfect printing environment for PETG, what are the factors of influence on printing quality
- Heating element to control environment inside the printer

Other
- RFID, what types of data and what happens with the data, language?

Further research

The steps taken for further research have been processed in the analysis part and were taken during the setup of the embodiment phase, so the results can either be found in chapter 5.1.1 or 5.3.
- RFID, what types of data and what happens with the data, language?
  - How can it be used and implemented?
- Existing solutions for process scanning
  - Project Kronos
  - Spaghetti detective
- Current carrier systems, usable when scaled upwards to match printing dimensions?
- Material crates, what exactly is needed for them (done in interview with J. Versteegh, Appendix E)
- Tracking material left on spool, sensor + RFID
- New material dispatched towards the printer

Prototyping

Prototyping will be presented in chapter 5.2.
- Printbed placement, removal and replacement
  - Remove printbed, add parts, return printbed and continue printing
- Carriage
  - Entering and leaving the printer
    - Precision placement
    - Returning the print to a printer
  - Design of the carriage, what is needed?
  - Removal of prints
- Heat curtains
  - Which works best
  - Effect on prints, when entering/leaving the printer
  - Shape of the door/curtain

Designing

Some of these design inputs can already be seen in chapter 5.1, others will be introduced with the renders in chapter 5.3.
- The printing carriage
- Material crates
  - Also look at how new materials are dispatched
  - Refilling the crates
  - Connection between crates & material feeder
- Curtains for the printing system
- Assembly station
- Scanning station
- Checklist for RFID
- Preheating of printbed location
- Relating sensor data to the product quality
- Easy access for maintenance (Look at maintenance chapter)
- Modular & scalable
- Adjust to production line (use examples from the field)

5.2 Prototyping

For the embodiment of the project two parts have been selected for prototyping. The door material (5.2.1) (which were meant to be used as curtains in stead of doors, but need some more ideation steps to work optimally) and the carriage (5.2.2). These prototypes will be used to prove and improve the working principles of the design and will be used for the final (concept) design presented in chapter 5.3.

5.2.1 Heat curtains

The concept design includes curtains through which the 3D-printed parts go after printing. The advantage of this idea is that it is a passive system, no motor is needed, while not taking up any space. This idea will be changed, why and how is reported in chapter 5.2.1.2 Redesigning. Chapter 5.2.1 will follow a paper type of layout on the research done, starting with an introduction, followed by materials & method, results and concluded with a discussion.

5.2.1 Research

Introduction

Ten samples for heat resistant curtains made by CEPRO© have been acquired (Figure 5.7 shows them numbered from 1 to 10). There is knowledge on their resistance of heat but not on how well they keep heat inside a chamber. The prototype is built to test the usability of curtains to replace doors, the results found will be used to make a redesign on the doors.

Materials and method

An isolated box was made with an opening small enough to fit the samples in front of it. Inside the box are two 5v heat mats. Inside and in front of the box temperature sensors have been installed to monitor the loss of heat. The setup is shown in figure 5.8.

The temperature sensors were controlled by an Arduino. The code and images can be found in appendix T.

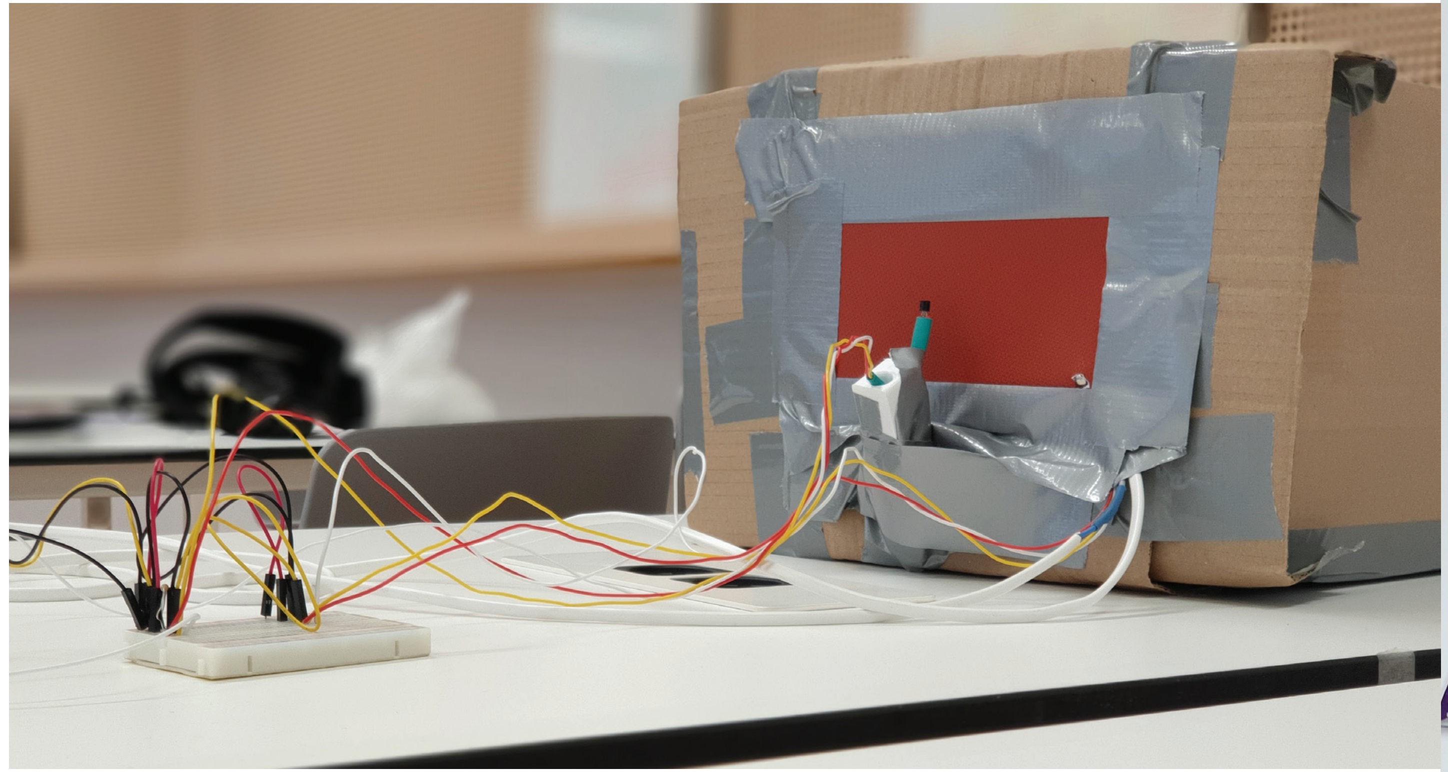


Figure 5.8 Heat curtain test set-up

Figure 5.7 Materials

For each of the curtains the box was heated for 5 minutes, with measurements starting at 36 degrees Celsius. And then left to cool down for about 5 minutes. After this initial round of testing the best 3 materials were selected for longer more precisely executed tests. All materials were photographed with an infrared camera during the tests, an overview can be found in figure 5.9.

In these more precise tests 12 measurements per material were done. The box is heated from 35 to 45 degrees Celsius starting from a temperature of 32 degrees Celsius to keep the parameters equal. Then the more important measurement was done, how much warmth is lost. The boxes were heated to 47 degrees and then the time was measured for cool-down from 46 to 42 degrees Celsius. Both measurements were done three times, with 2 sensors, one inside, kept in place by a 3D-printed part to always have the same location and one sensor placed against the material on the outside, making a total of 12 measurements per material.

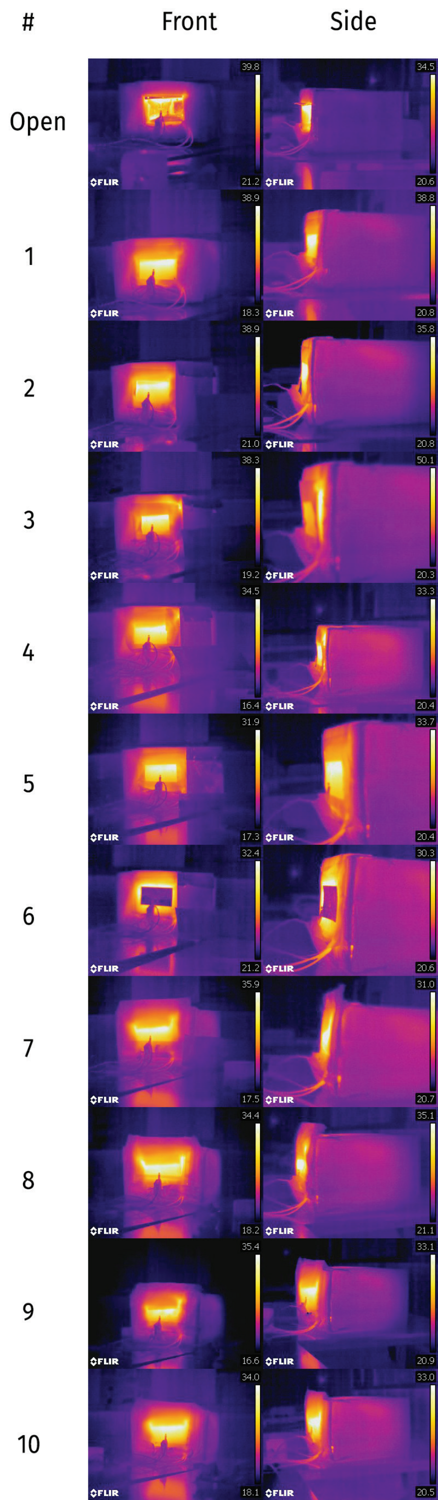


Figure 5.9 Infrared images

Results

Figure 5.10 displays the results from the first round of tests with all 10 materials. Warming the enclosure from 36 degrees Celsius over a period of 5 minutes and then leaving it to cool down for 5 minutes. It was found that materials 1, 2 and 6 scored best, these were then used for the more precise tests.

Figure 5.11 shows the most important results of these tests, the full results of all tests can be found in Appendix U. Material 1 (named Cratos, able of withstanding temperatures up to 600 degree Celsius) kept warmth inside the room best and was therefore selected as material for the concept. The material is made from glass fibre with a two-sided silicone rubber coating. It is oil, grease and acid resistant,

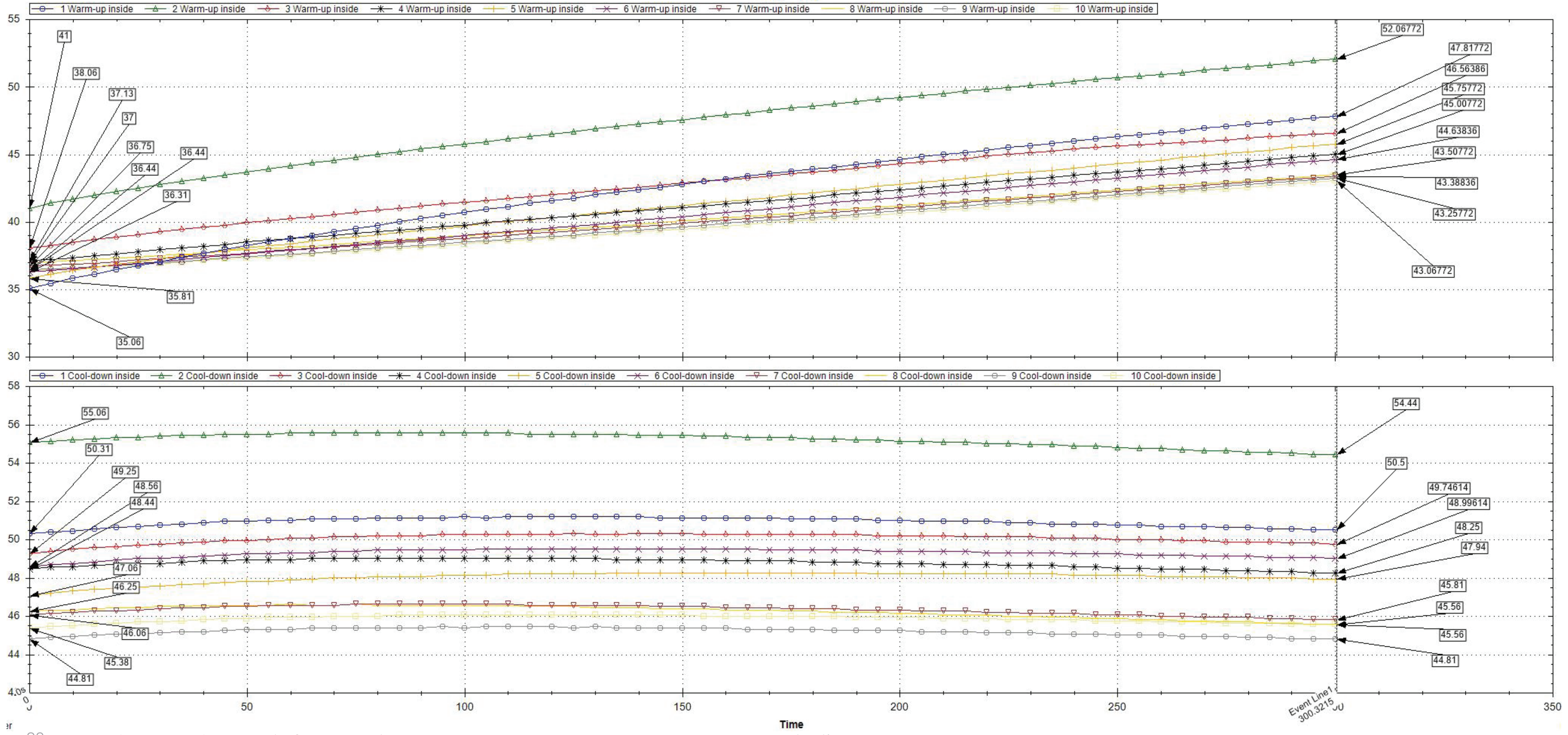


Figure 5.10 First round of tests result

Discussion

Cratos, the material chosen, is priced at 35 Euro for 25 square meters (at lpmw.nl) which is enough to replace about 80 doors (double coated) sized 500 by 300 mm. This makes it an extremely cheap alternative to acrylic doors.

Upon discussing the idea of hanging curtains in front of the printers and moving the just printed part through concerns arose.

The main concerns are the fact that a part, which is still hot, is moved against a material, potentially damaging the part. The curtain will wear out rapidly as each time a carrier passes some particles of the coating will be removed. The material would keep hanging on the carrier, harming the process. Therefore, it was found necessary to redesign the door solution.

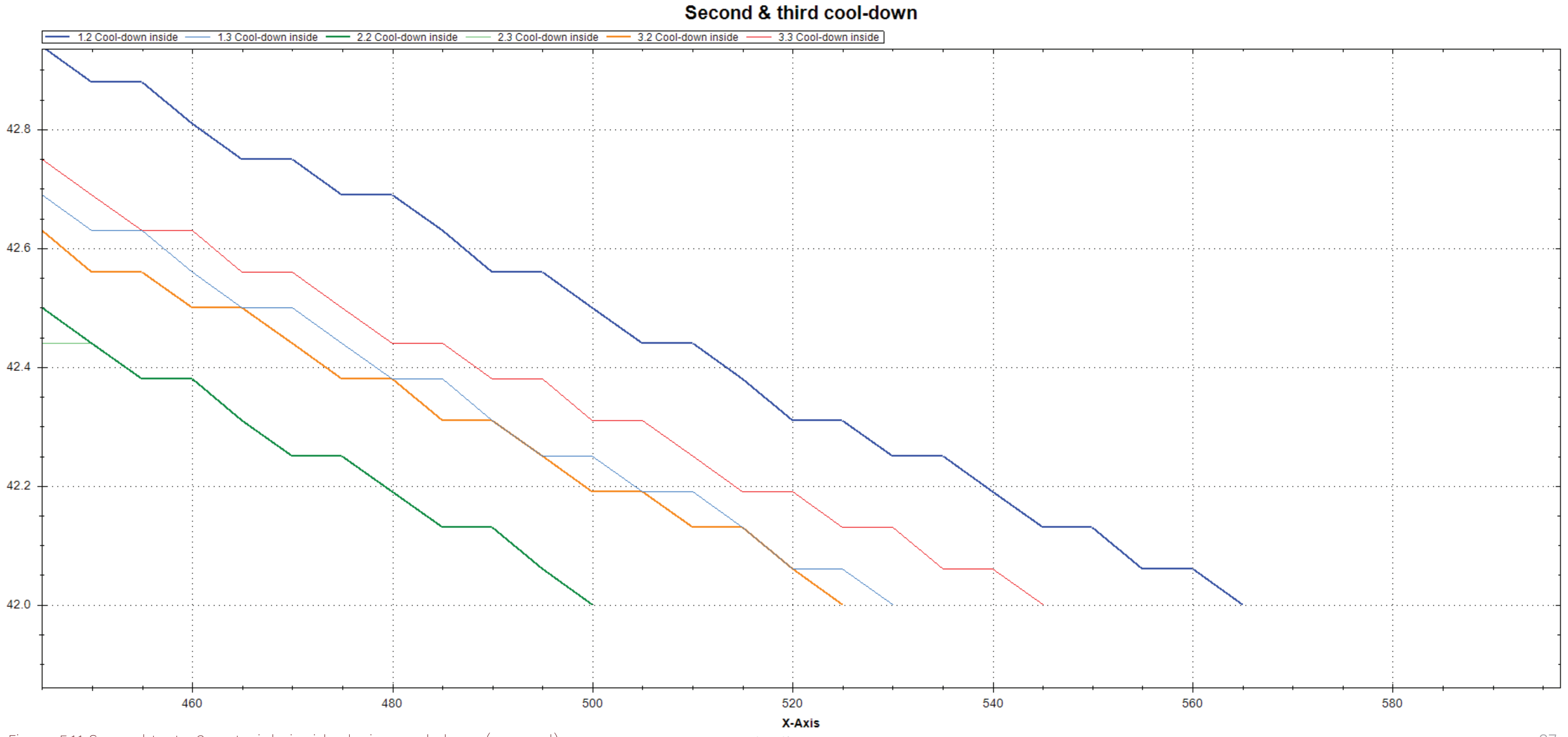


Figure 5.11 Second tests, 3 materials inside during cool-down (zoomed)

5.2.1.2 Redesign

It was deemed necessary to rethink the way the printer units were enclosed. With the new knowledge a new round of ideating was done for the opening. Some requirements and wishes for this system were defined.

Requirements:

- May not hinder the working principles of the concept
- Must work with the conveyor belt underneath
- Must fully enclose the printer units
- May not touch the prints
- No more space used on the sides of the printing units (no sliding doors towards the side)

Wishes

- Take up as little space of the printing unit as possible (more space makes it harder to fully control temperatures
- Passive system (so no extra motor is required)

During the ideation various systems were looked into. As a passive system was wished, the goal was to come up with a system that would be opened by pushing the carrier against it. Four rod mechanisms were researched to minimize the space it would require (figure 5.12).

A spring is needed to automatically (and passively) close the doors after the carriage has passed. This increases the force required to open it. Since the carrier is on a conveyor belt this will not work, as the carrier could be moved or titled by the doors which would compromise the entire system because precise placement is key for the concept to work.

This meant back to the drawing board again. The wish of a passive system was scratched as it is prone to error. The new door system can be an active one. It had to take up as little space as possible. Swinging doors have to move over the conveyor belt, leaving some space open. Therefore, the decision was made to develop rolling curtains. The material researched in this chapter can still be used for this. The curtain falls precisely between the two conveyor belts. Chapter 5.3 will show some renders on how this works.

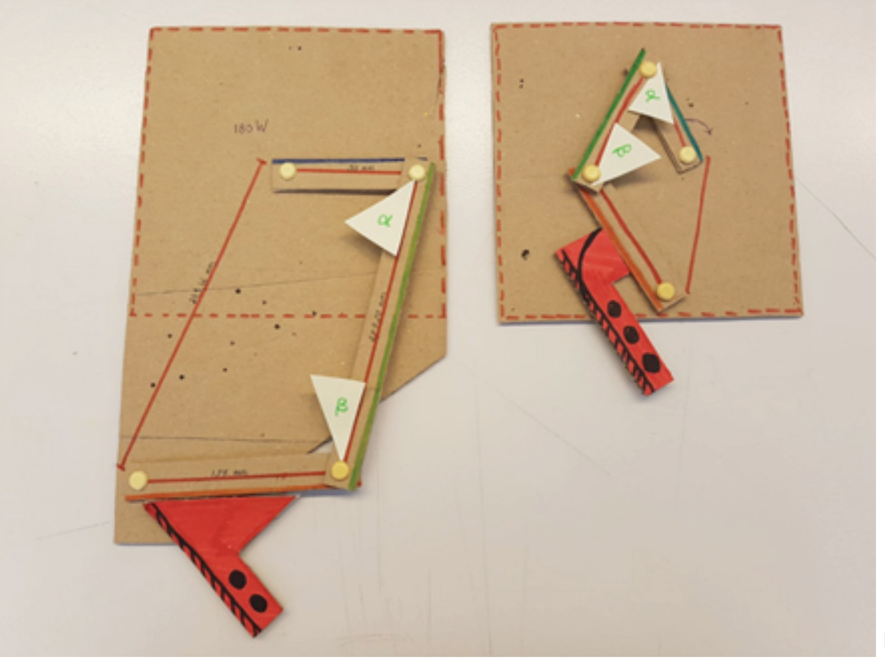


Figure 5.12 four rod mechanism prototype

5.2.2 Carrier

The key enabler of the carrier system is the kinematic coupling for precise placement of the printbed. To test whether this actually works a kinematic coupling was prototyped for the printbed of a Prusa i3 mk3 3D printer (5.2.2.1). Tests were performed to see if the kinematic coupling is precise enough to remove and place the printbed. The exact precision of the kinematic coupling was measured in chapter 5.2.2.2. And finally, a prototype of the carrier was built along with a conveyor belt to test the placement principle (5.2.2.3).

5.2.2.1 Kinematic coupling prototype

Research was done on connectors for the printbed. Kinematic couplings were found to be the most accurate way to make a connection while keeping the ability to easily disconnect the coupling. Figure 5.13 shows data on the precision of kinematic couplings. Having a drastically lower tolerance than other precision coupling methods. An overview of kinematic coupling as proposed by the MIT research group:

- When a component is constrained by a number of points equal to the number of degrees of freedom, it is said to be exactly constrained.
- Low-Medium Force Precision Applications
- Do Not Allow Sealing Contact
- Moderate Stiffness
- Moderate Cost
- Excellent repeatability
- 1/4 micron common
- On order of surface Finish

Inspiration for the use of kinematic coupling came from E3D's tool changer. E3D is producing a tool changer for FDM printers (Figure 5.14) where different tool heads can be attached to the extruder part. For instance, to attach a sensor for bed leveling, afterwards detaching it, making it lighter which is better for the printing process. This of course has to be

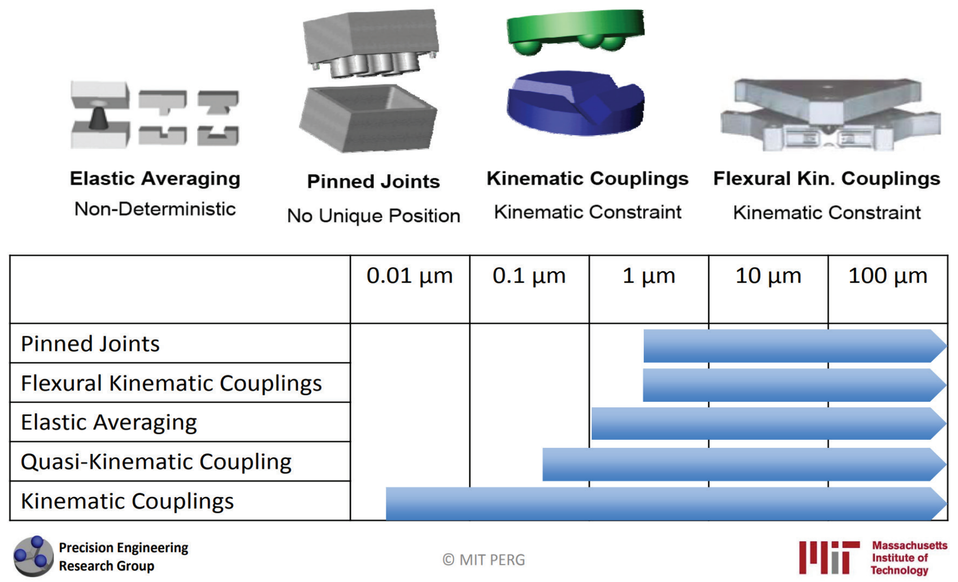


Figure 5.13 Review of coupling methods (©MIT PERG)

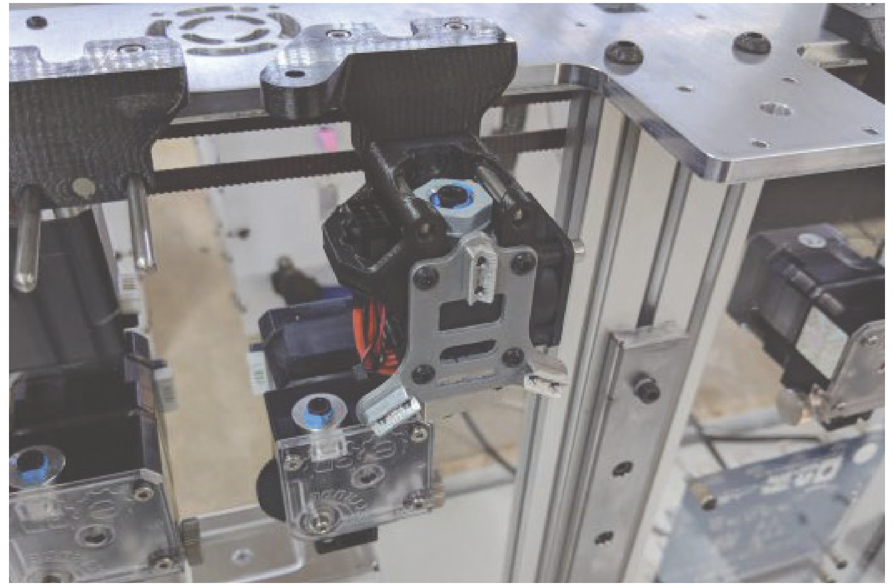


Figure 5.14 Kinematic coupling by E3D

done at as low tolerances as possible, because otherwise the calibration done is useless.

The tool changer by E3D contains a locking mechanism, otherwise the tool would fall off. The goal for the kinematic coupling in the Ultifact is to remove the locking mechanism and use gravity to keep the printbed in place.

The first design for the carrier features two kinematic couplings, one for the connection between the printer and printbed and one for the connection between the printbed and the carrier (figures 5.15, 5.16 and 5.17 show how this was intended to work).

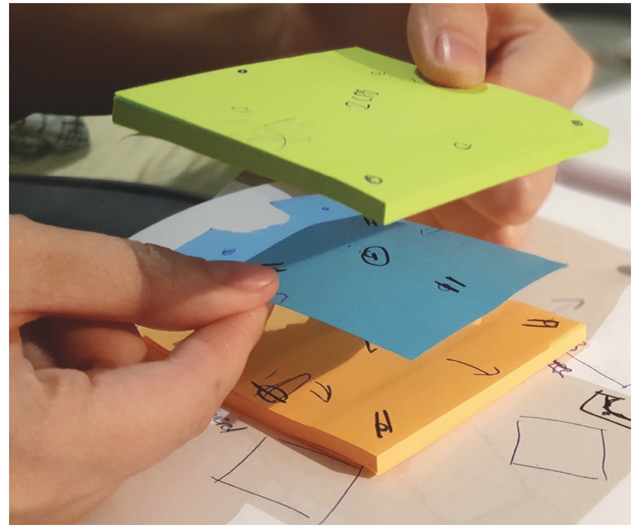


Figure 5.15 Double kinematic coupling making it fit

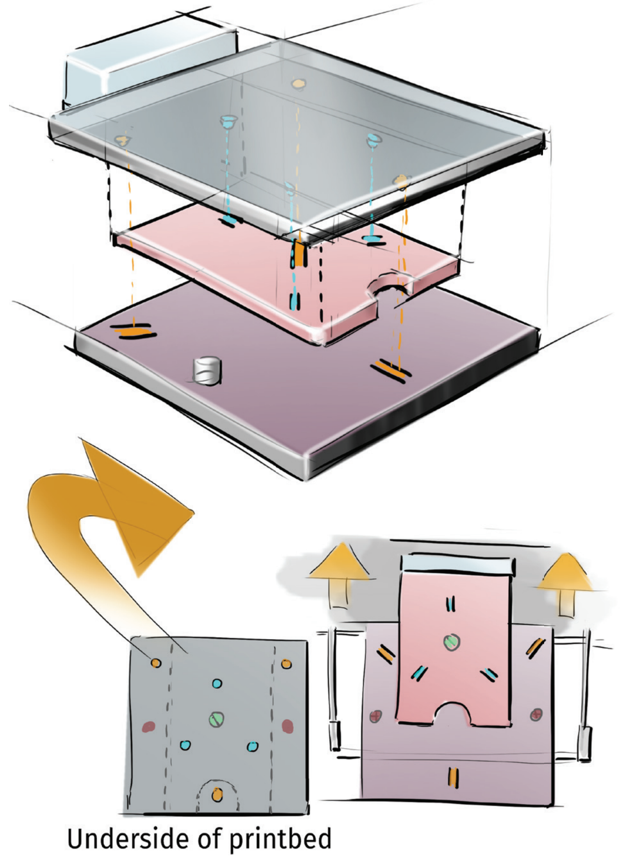


Figure 5.16 Double kinematic coupling system

The coupling works well without a locking mechanism when the movement is restricted to up and down motions. However, if a carrier moves through the factory it has a high chance of being knocked off the coupling. With this in mind it was decided that, in order to not overly complicate the carriage, the entire carriage will be lifted by the printer (chapter 5.3 reports on the specifics of the plate in the printer and how much weight it can hold). Since the z motion in Ultimakers is done with a threaded rod, the added weight will not be a problem for the mechanism.

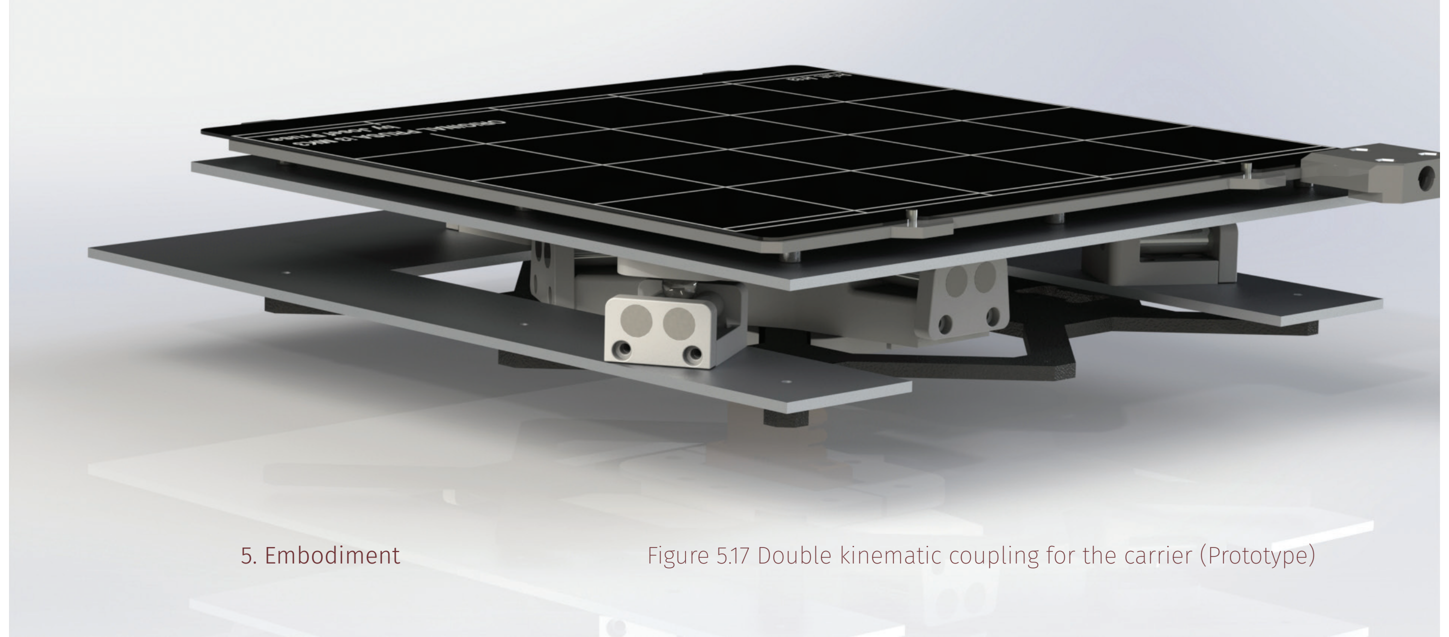


Figure 5.17 Double kinematic coupling for the carrier (Prototype)

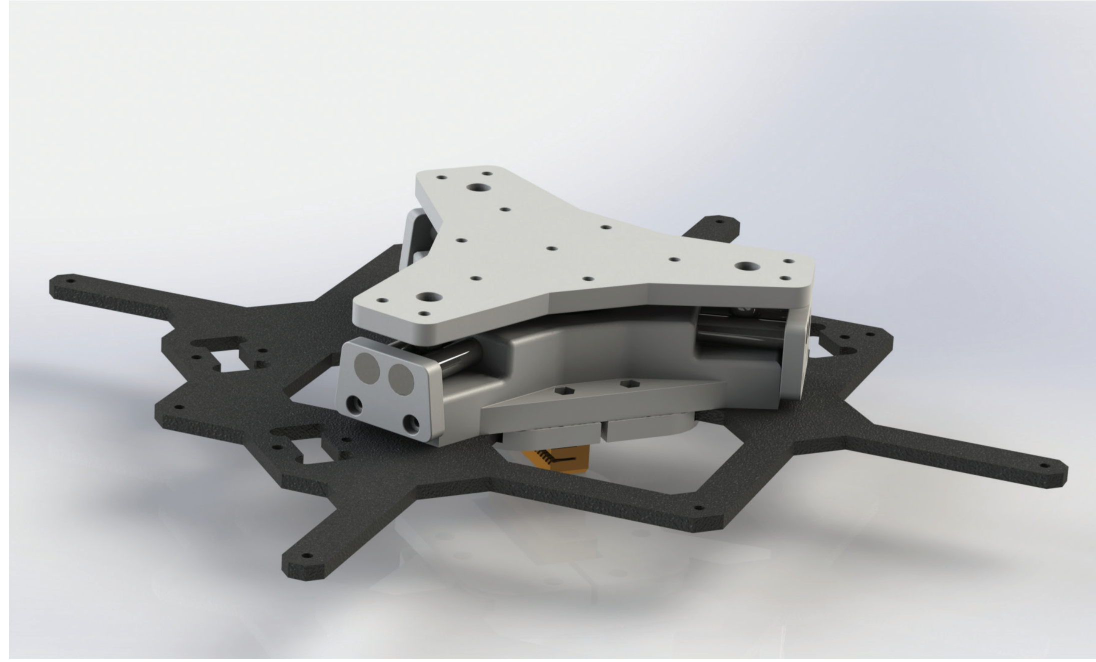


Figure 5.18 Digital model of the kinematic coupling on the Y-carriage

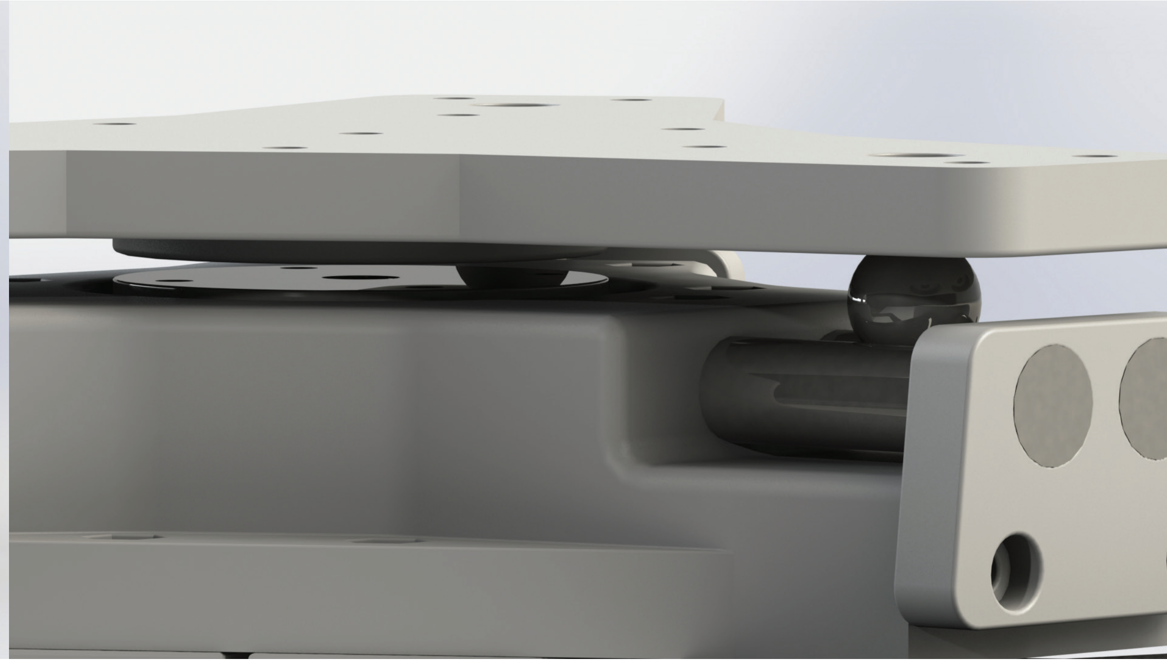


Figure 5.19 Detail of the kinematic connection

Materials & Method

To test the kinematic coupling a digital model was first made to fit all the parts on the 3D-printer, renders including the Y carriage of the printer can be found in figure 5.18 and 5.19.

The resultant prototype is shown in figure 5.20. Appendix V shows how the kinematic coupling prototype was produced. This was placed on the Prusa FDM printer. Which is printing with PETG for the tests. The first tests will be done to find out how well the kinematic coupling works at resuming prints when products are

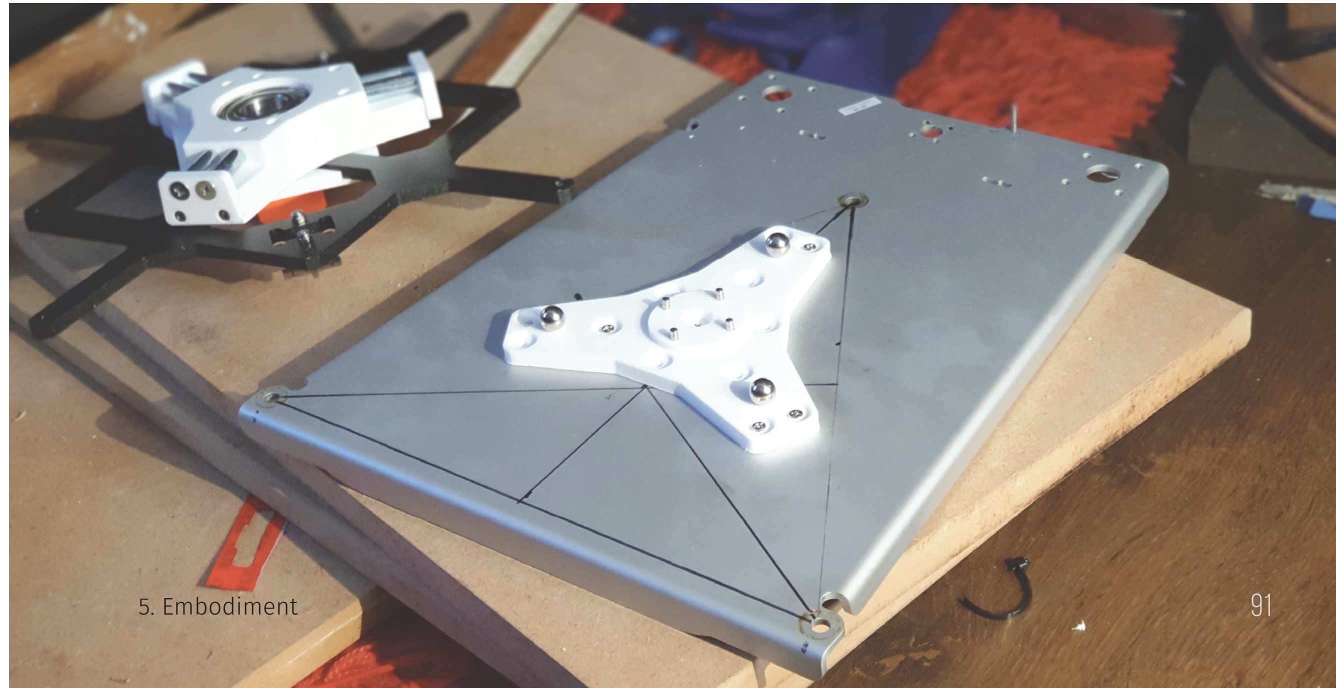


Figure 5.20 Kinematic coupling prototype

embedded. this is done by pausing the prints with a command in the Gcode (a command for changing material is added making the printer pause at that part). Removing the printbed from the printer and embedding the parts, bogs and screws in this case. Pausing prints and then removing material causes the pressure in the extruder to change. To overcome problems this causes a purge tower will be printed next to it, so the extruder can first start extruding on the purge tower before moving to the part. A block will be printed this way with the printbed removed from the printer for 30 minutes each pause.

Results

Removing the printbed during the process was possible with the prototype. Figure 5.21 shows the process where bogs were embedded and the result meaning Kinematic coupling has a precise enough placement to allow removal of the printbed. There are some weaknesses in the adhesion between the last line before and the first line after a pause.

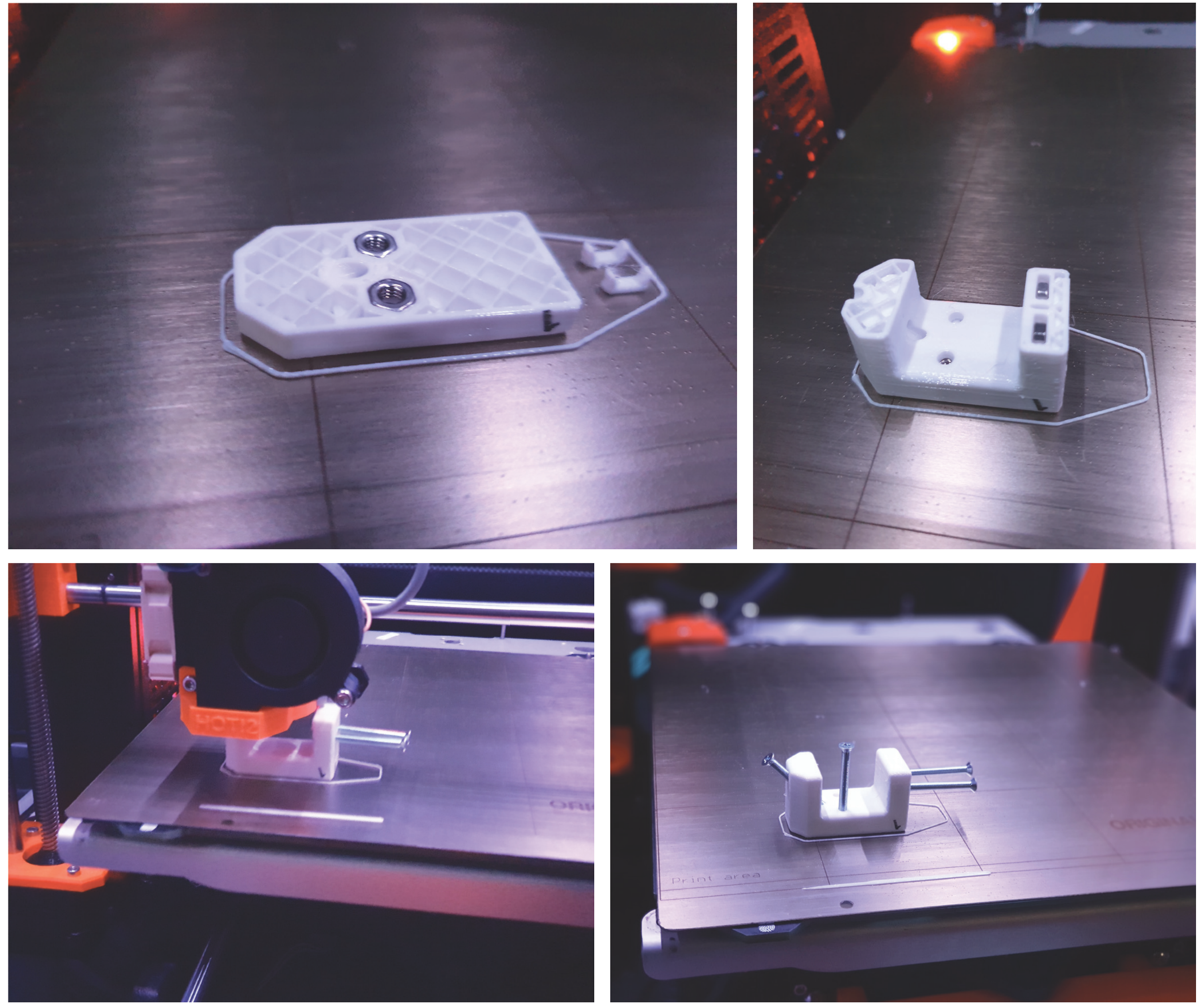


Figure 5.21 Results embedding test

The test with the purge tower was done to see if the adhesion can be improved an whether it is caused by the placement of the heat bed or the removal of filament from the extruder. Figure 5.22 shows the process of this test. The black lines on the side indicate when a pause of 30 minutes in the process was held. It was found that the purge tower did indeed help with layer adhesion. After the print was finished the purge tower was already broken at one of the pause layers, while the paused layers in the main block had just as good an adhesion as the rest of the layers.

Discussion

It was found that kinematic coupling is a good way to remove the printbed from a printer and return it. No calibration is needed after pauses of 30 minutes as long as the pressure in the extruder is maintained and controlled. For longer pauses (multiple) the top layer will need new calibration because the product will have changed due to thermal shrinkage. Keeping the heat bed at temperature is key here, otherwise the prints will release.

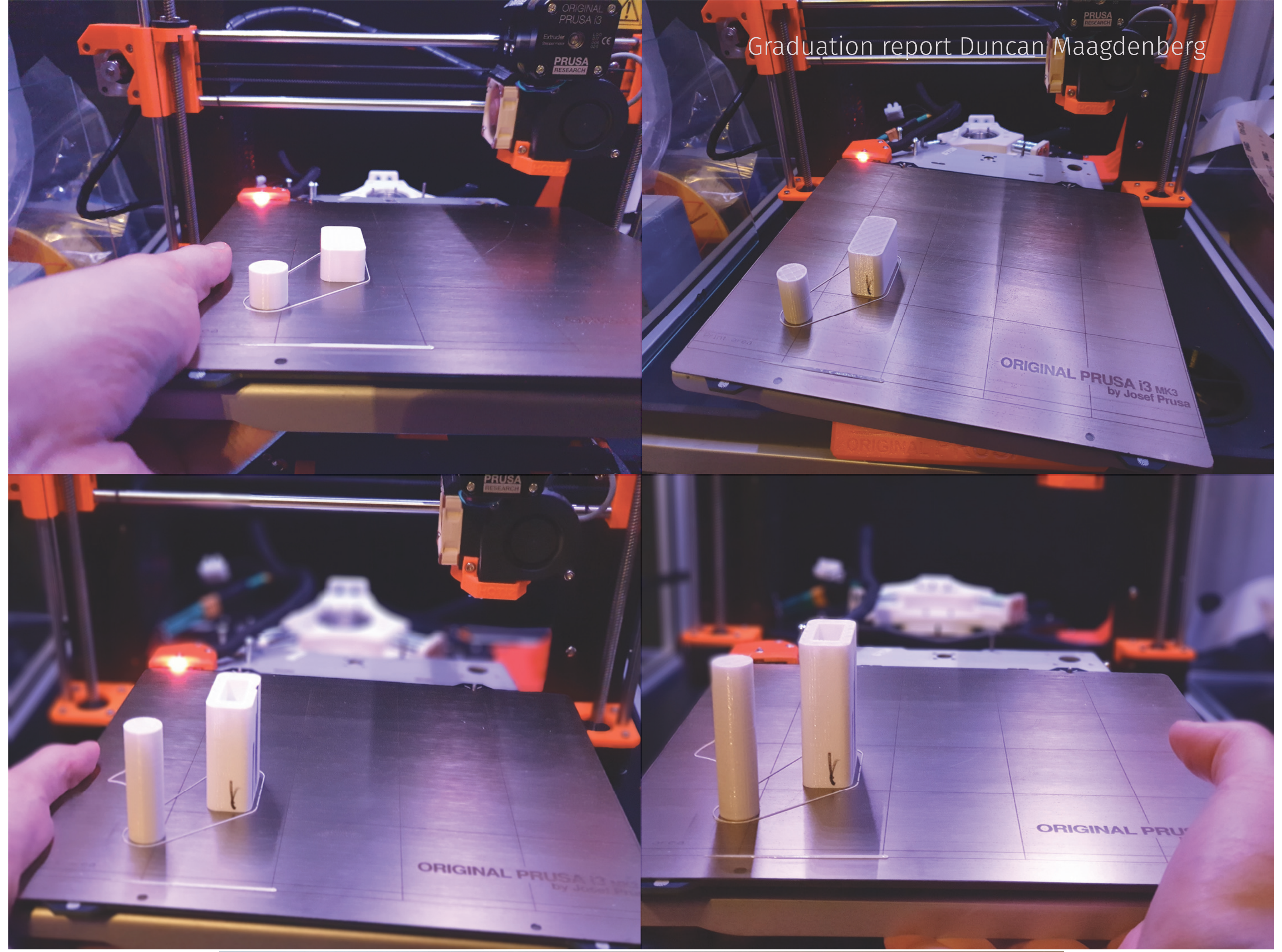
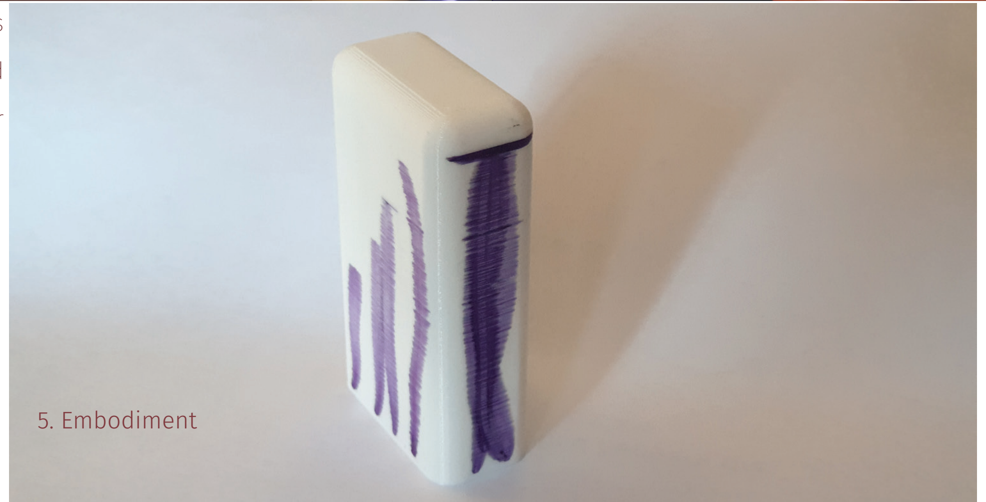


Figure 5.22 Results removing printbed with purge tower



5.2.2.2 Precision

Measurements were done to analyze the tolerance of the kinematic coupling prototype. The maximum deviation measured was 0.02 mm, which is not as good as the results presented by MIT. This deviation can be caused by to the material for measurements as well, figure 5.23 shows the set-up during the measurements. After multiple failed attempts this did work. The list of results can be found in appendix W. The measurements were done against the side as well. There a deviation of 0.00 was found, so more precise tools are required to define the precise deviation of the prototype. For the prototype itself it was decided that a tolerance of maximum 0.02 is more than sufficient for the prototype since it is in the most extreme case, just 10% of a layer height.

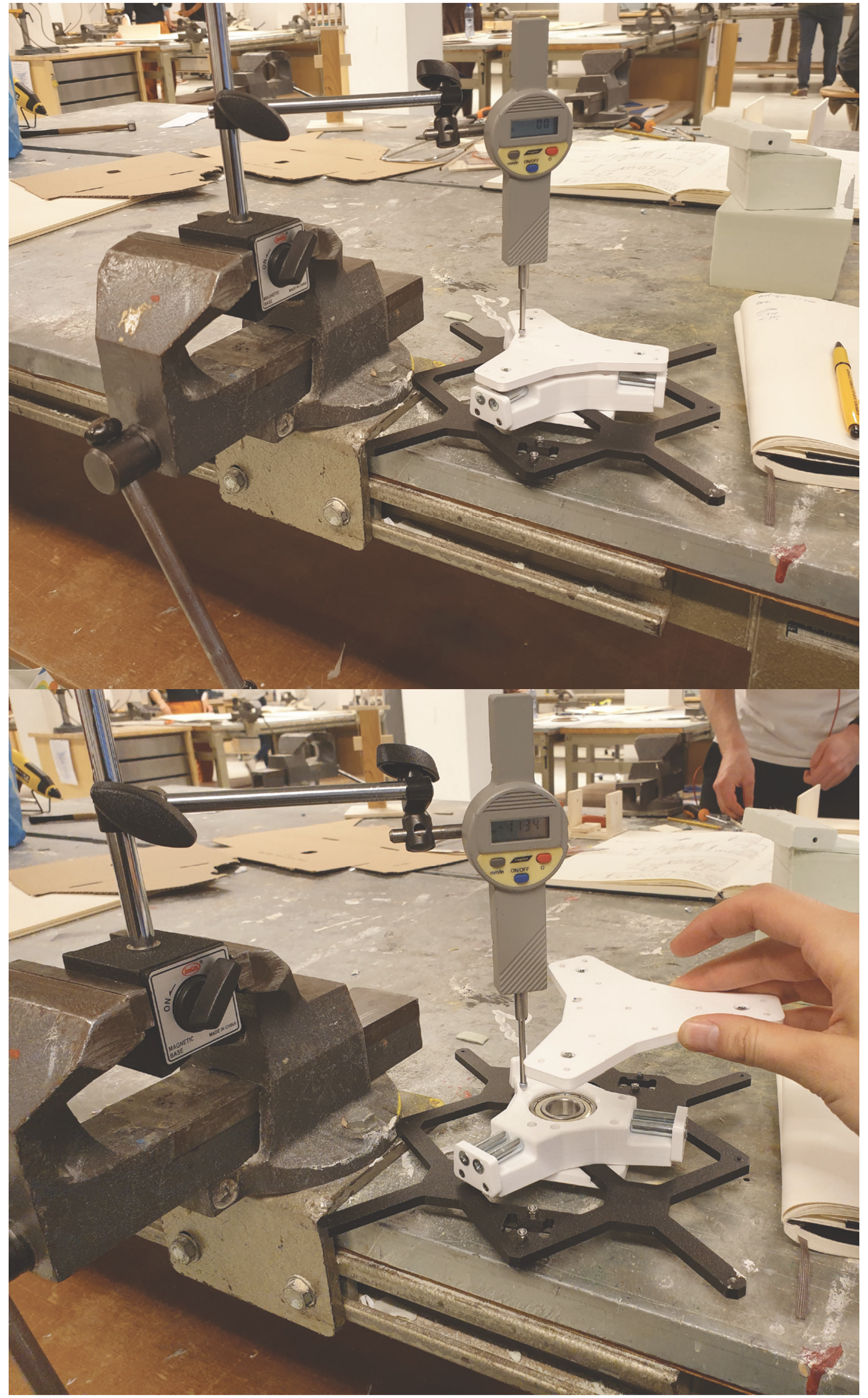


Figure 5.23 Measurement set-up

5.2.2.3 Carrier prototype

A prototype of the carrier was made with a conveyor belt to prove the working principle of the carrier concept. Figures 5.24 to 5.28 show the interaction of the carrier system with the Z-axis of an Ultimaker 3 (stripped down).

The carrier is placed on the conveyor belt and moved to the z-axis plate of the Ultimaker

Figure 5.24 Carrier prototype

Figure 5.25 Carrer in front of Ultimaker Z-axis

The conveyor belt aligns the two parts of the kinematic coupling. The plate of the Z axis moves in between the bottom plate of the carrier and the heat bed. Once the Z-plate of the Ultimaker is lifted it lifts the entire carrier as well. with the kinematic coupling the placement has an accuracy of 0.02 mm.

When the print is done, the Ultimaker Z-axis is lowered and the carrier is placed on the conveyor belt. The Z-axis is lowered enough so it is not in contact with the carrier anymore and the carrier can be moved away from the printer by the conveyor belt.

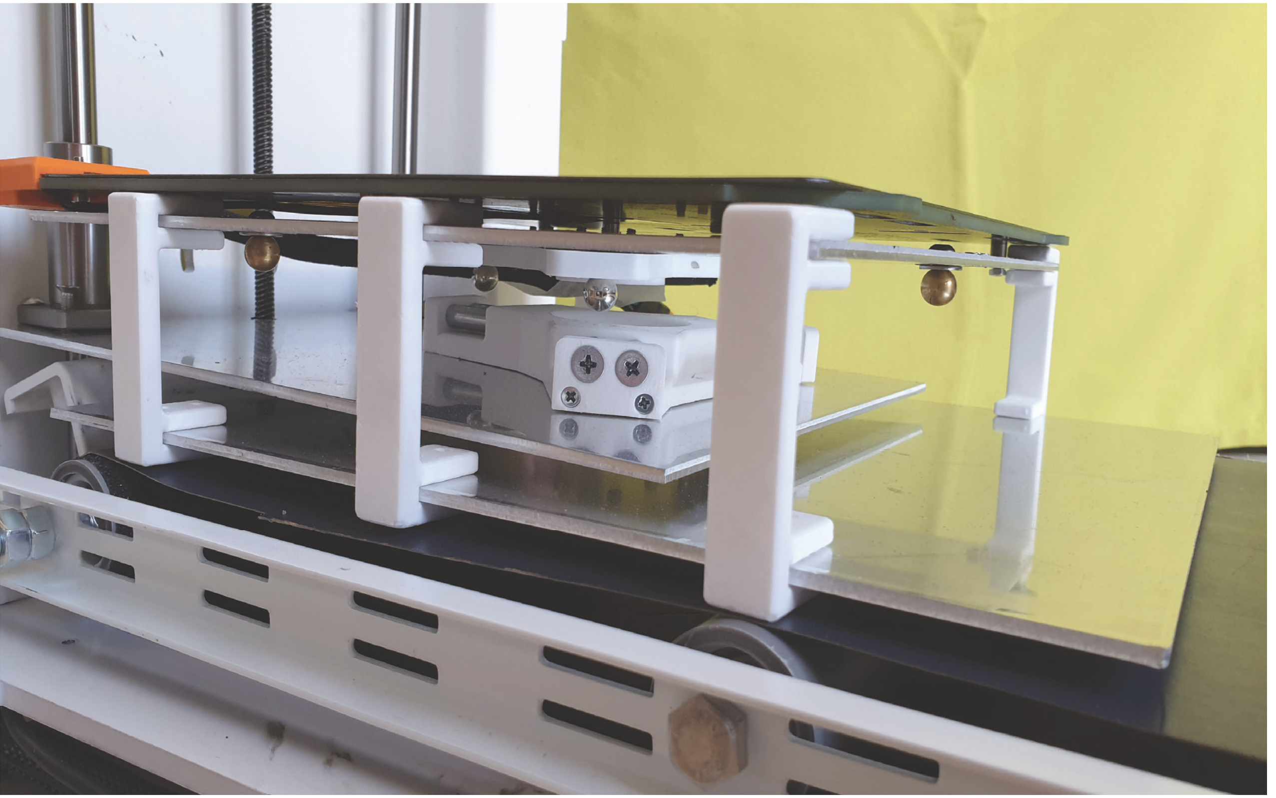


Figure 5.26 The carrier aligned with Z-axis plate

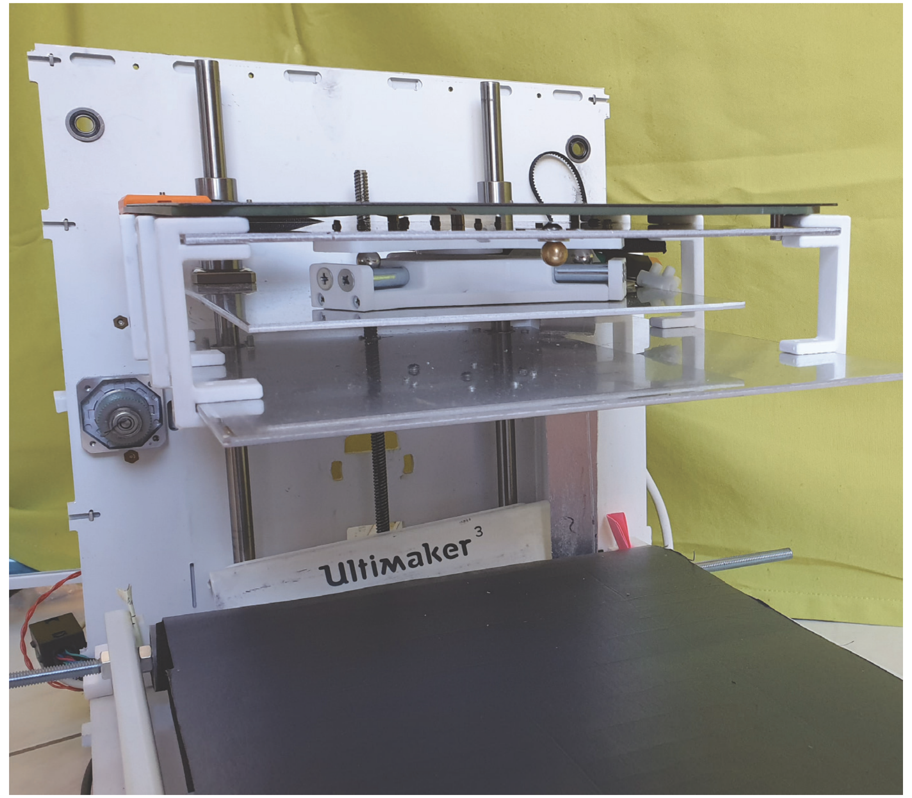


Figure 5.27 Entire carrier is lifted

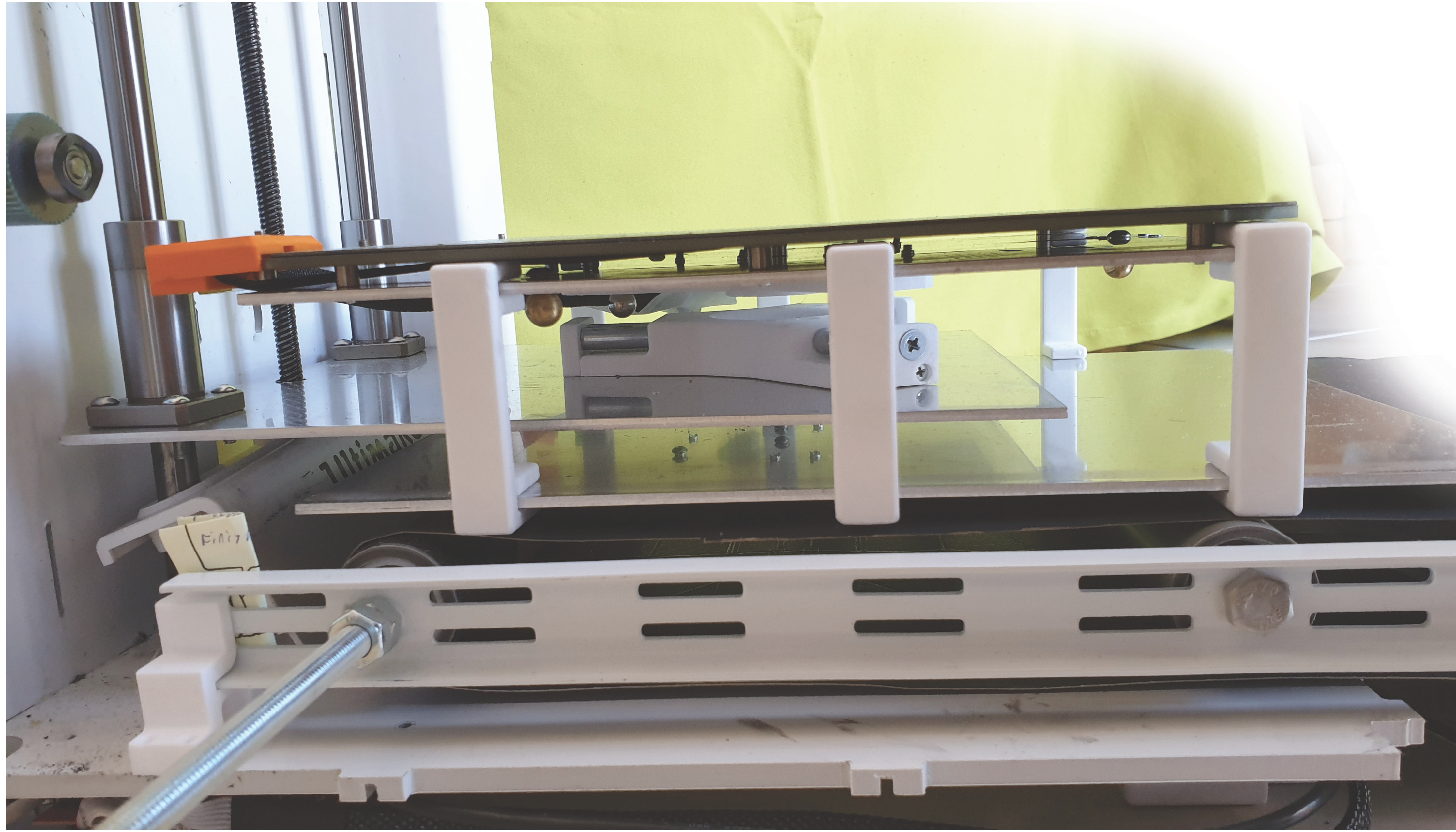


Figure 5.28 Carrier returned to conveyor belt

5.3 Redesign, detailed features

This Chapter will report on the final (concept) design of the UltiFact 4.0 presented in renders. Chapter 5.3.1 shows the redesigned features of the Ultifact, and describes how the conveyor system works, the system is modular and the material is supplied. Chapter 5.3.2 shows the modularity and scalability of the Ultifact. The design of the carrier is presented in chapter 5.3.3 and the curtains in 5.3.4.

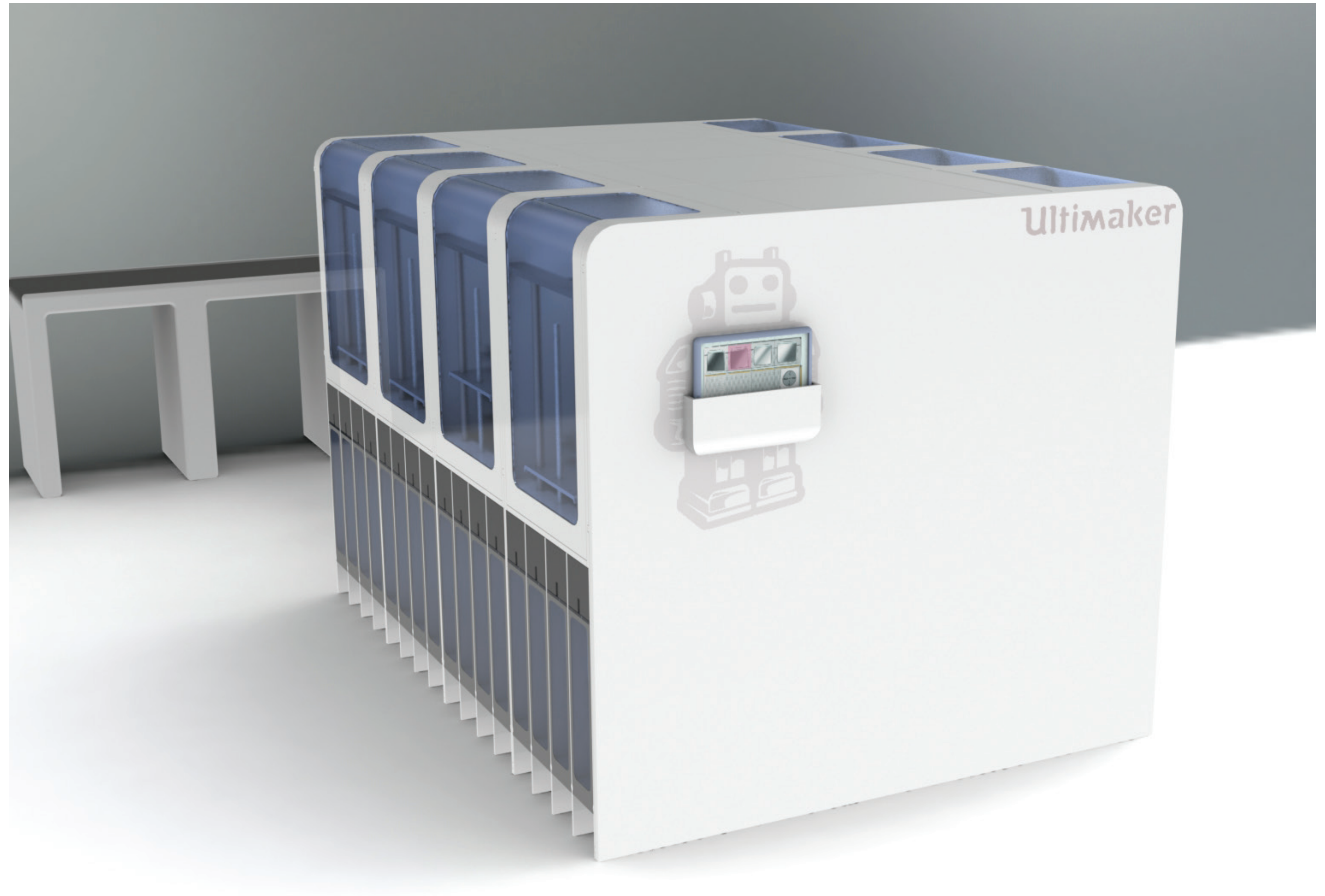


Figure 5.30 Control panel of the UltiFact 4.0

5.3.1 Redesign features

The features that have been redesigned in comparison to chapter 5.1 will be presented here. Figure 5.29 and 5.30 present The UltiFact 4.0. New features are listed below.

Hatch for maintenance

The hatch has been improved in the way it opens. By swinging fully up, an operator is able to reach all the required spots of the printer he is working on.

Location of tablet

The location of the tablet has been moved to the side opposed of the entrance, this place is more in reach as it is not constricted by a passing product line. A tablet has been included as control panel so the operator can take it with him to the printing unit he is working on and can directly receive information on what has to be done.

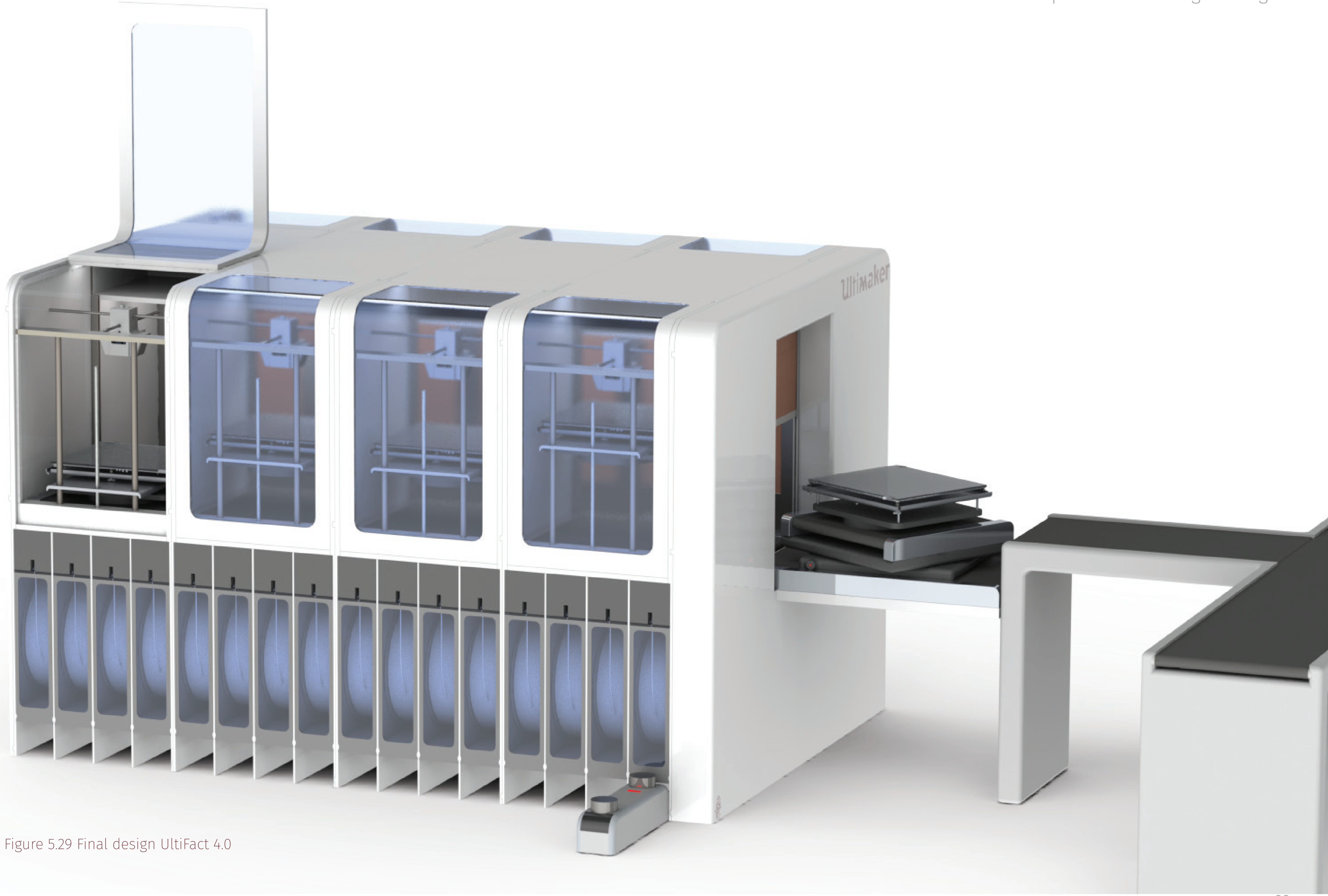


Figure 5.29 Final design UltiFact 4.0

The conveyor system

Figure 5.31 shows the "carrier carrier" system. A system to get the printbeds in the correct printer has been developed. The precise way of operation is presented in chapter 5.3.3 (Carrier). It is a conveyor belt on a rotating platform that is on a conveyor belt. This has been chosen because it is a simple and reliable solution to the fact that the printbed has to be oriented in the correct direction (for the kinematic coupling). The system has to be modular, multiple belts can be placed in a chain without issues. Lastly, the carrier has to move in another direction than the conveyors do, so a second conveyor belt is added. Each printing hub only requires one of the 'carrier carrier' systems. It contains sensors that read whether the printbed is positioned correctly.

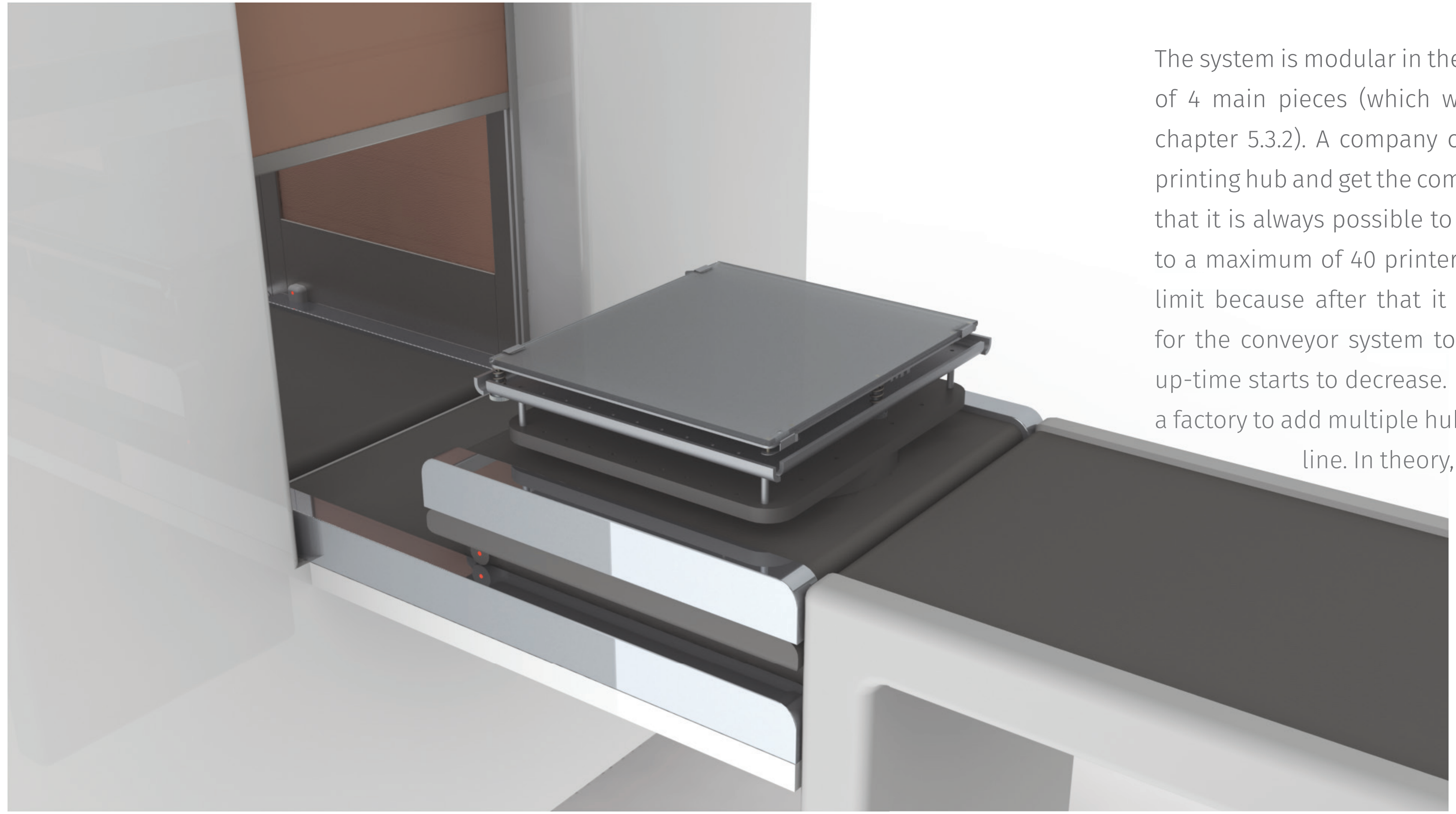


Figure 5.31 "Carrier carrier" system

Modularity

The system is modular in the fact that it consists of 4 main pieces (which will be presented in chapter 5.3.2). A company can decide to buy a printing hub and get the complete package. After that it is always possible to scale to the hub up to a maximum of 40 printers per hub. 40 is the limit because after that it becomes too much for the conveyor system too process, meaning up-time starts to decrease. But it is possible for a factory to add multiple hubs to the production line. In theory, making the number of printers that can be implemented in a production line infinite.

Material boxes

The material robot system still works the same as presented in chapter 5.1. Figure 5.32 shows how this will work.

With the estimation that 1kg of material can be printed in about 80 hours of continuous printing only one robot is required to maintain 40 printers. In the worst case, it will take the robot half an hour to replace a box, it will still have one and a half hour left between changes. Having to replace a box every 2 hours.

Autonomous robots are implemented in various industrial settings, for example amazon distribution centers, and are proven to work.

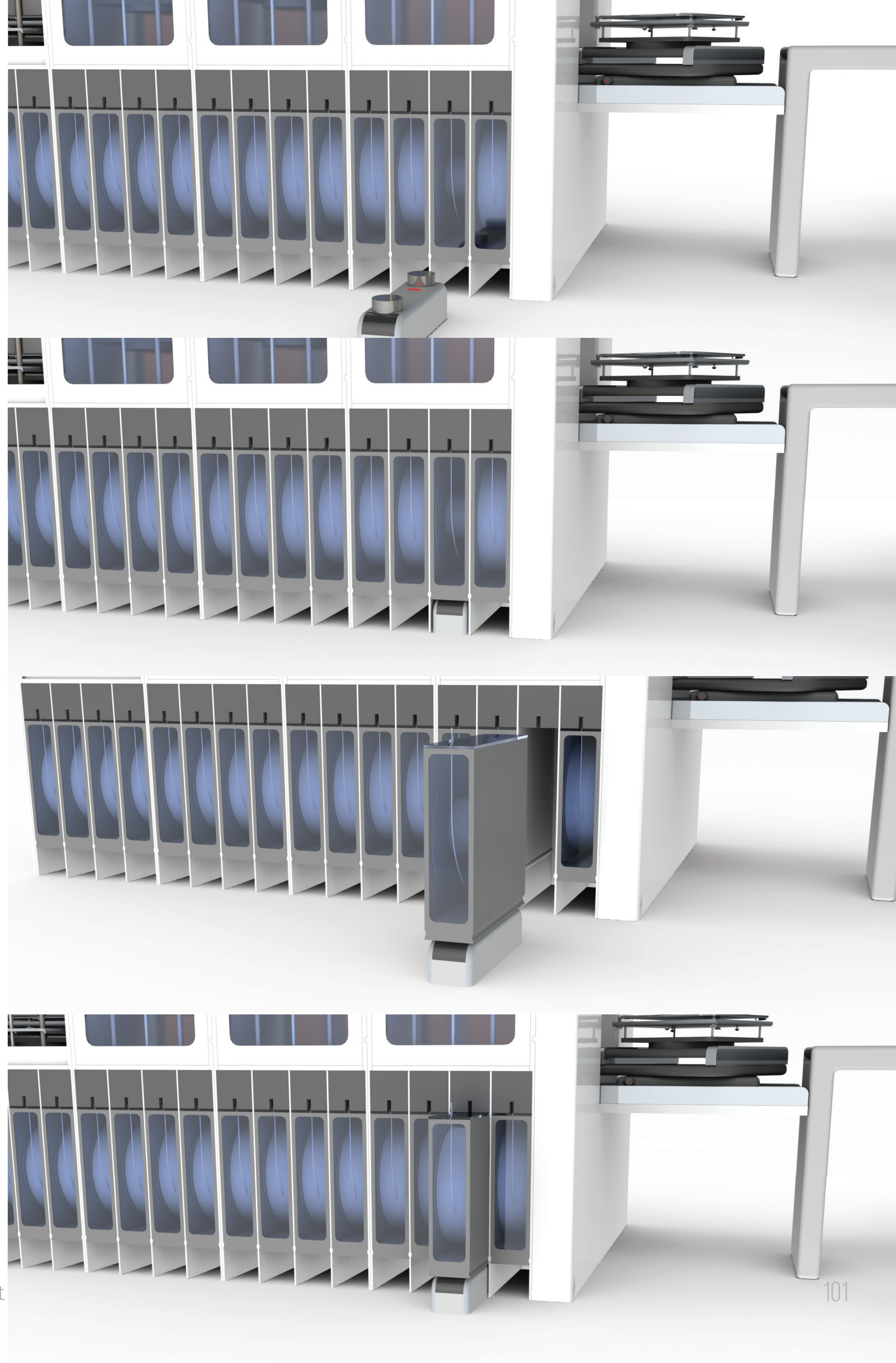


Figure 5.32 Working principle of material robot

5.3.2 Modularity & scalability

There are 4 main units that make up the UltiFact 4.0 and allow it to be a scalable system. They will be discussed in this chapter along with what happens if a printer malfunctions.

The main units are the center unit (5.33), the Printer unit (5.34), the entrance unit which includes the carrier carrier (5.35) and the control panel (5.36). Each hub consists of at least two printing units and one of the rest. To scale the hub more printers can be added. For each two printers that are added, one center unit is required.

The center unit consists of a conveyor belt, that brings the conveyor to the required location. Sensors that sense if the carrier carrier has reached the required position. The rolling curtains are attached to the center unit, so a printer can be removed without warmth escaping the hub.

The printing unit features compartments for 4 material boxes (two main material slots, two support slots). The printer itself has the same technology equipped as the S5 does. Each printer comes with two printbed carriers (5.37). More on those in chapter 5.3.3. A conveyor belt at the bottom places the carriers at the right location to be lifted by the Z- axis.

The entrance unit has its own rolling curtain to maintain the temperature in the entire hub when printbeds are not being replaced.

The control panel closes off the rear (or front depending how you look at it) of the hub it has a docking station for the tablet that is used during maintenance, repairs and for monitoring.

Figure 5.33 Center unit

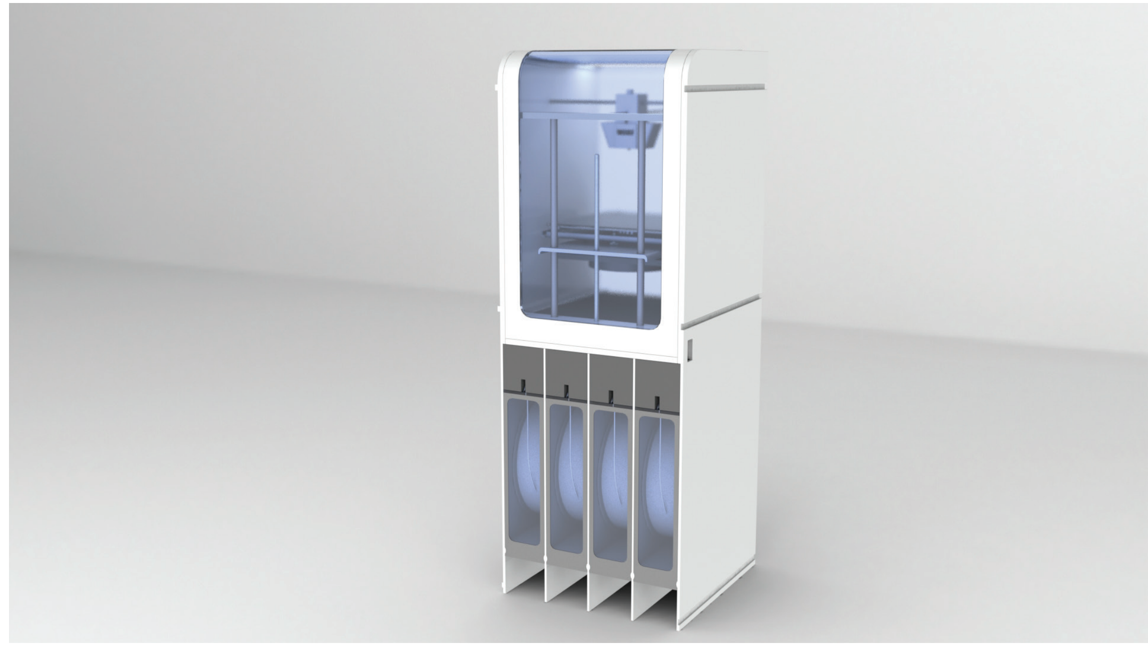


Figure 5.34 Printing unit

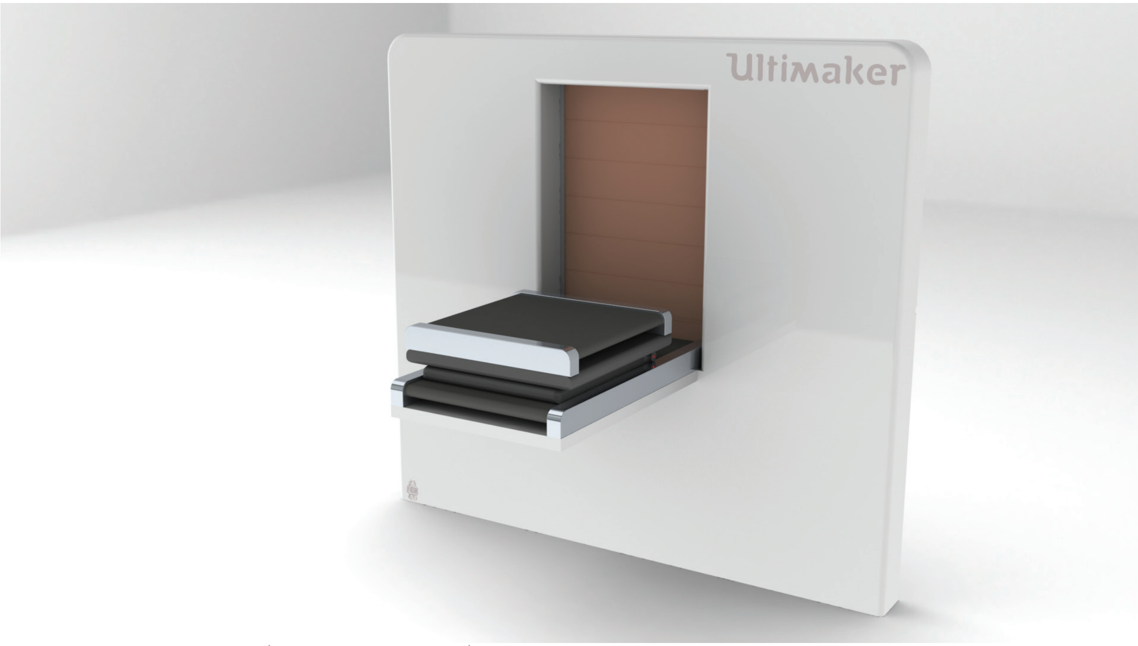


Figure 5.35 Entrance unit (with carrier carrier)

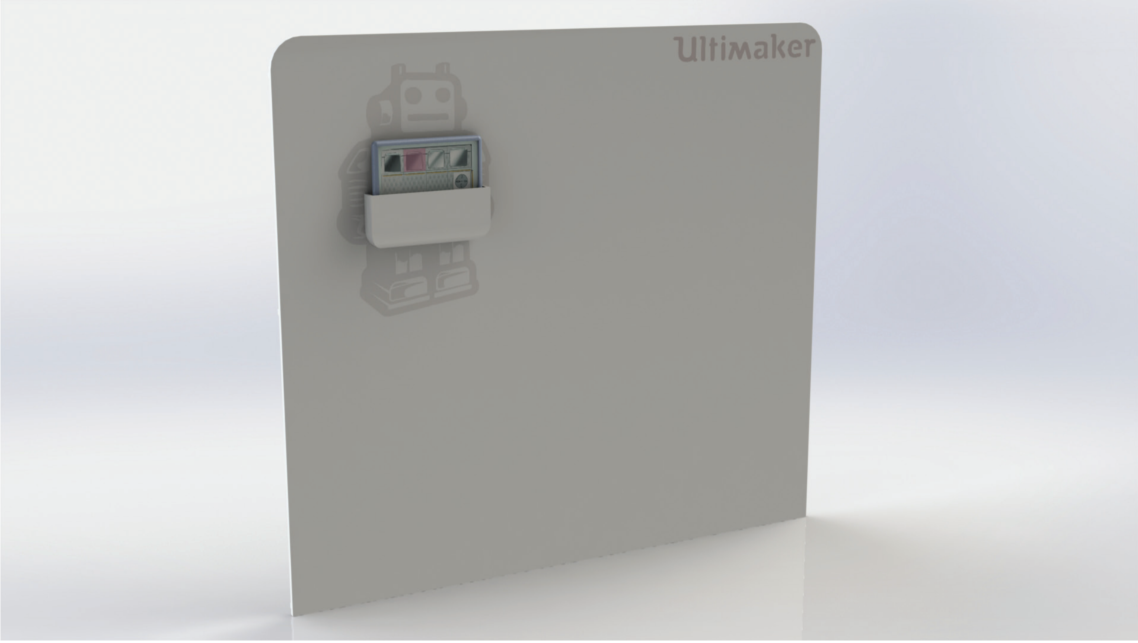


Figure 5.36 Control panel (with tablet)

Figure 5.37 Printbed carrier

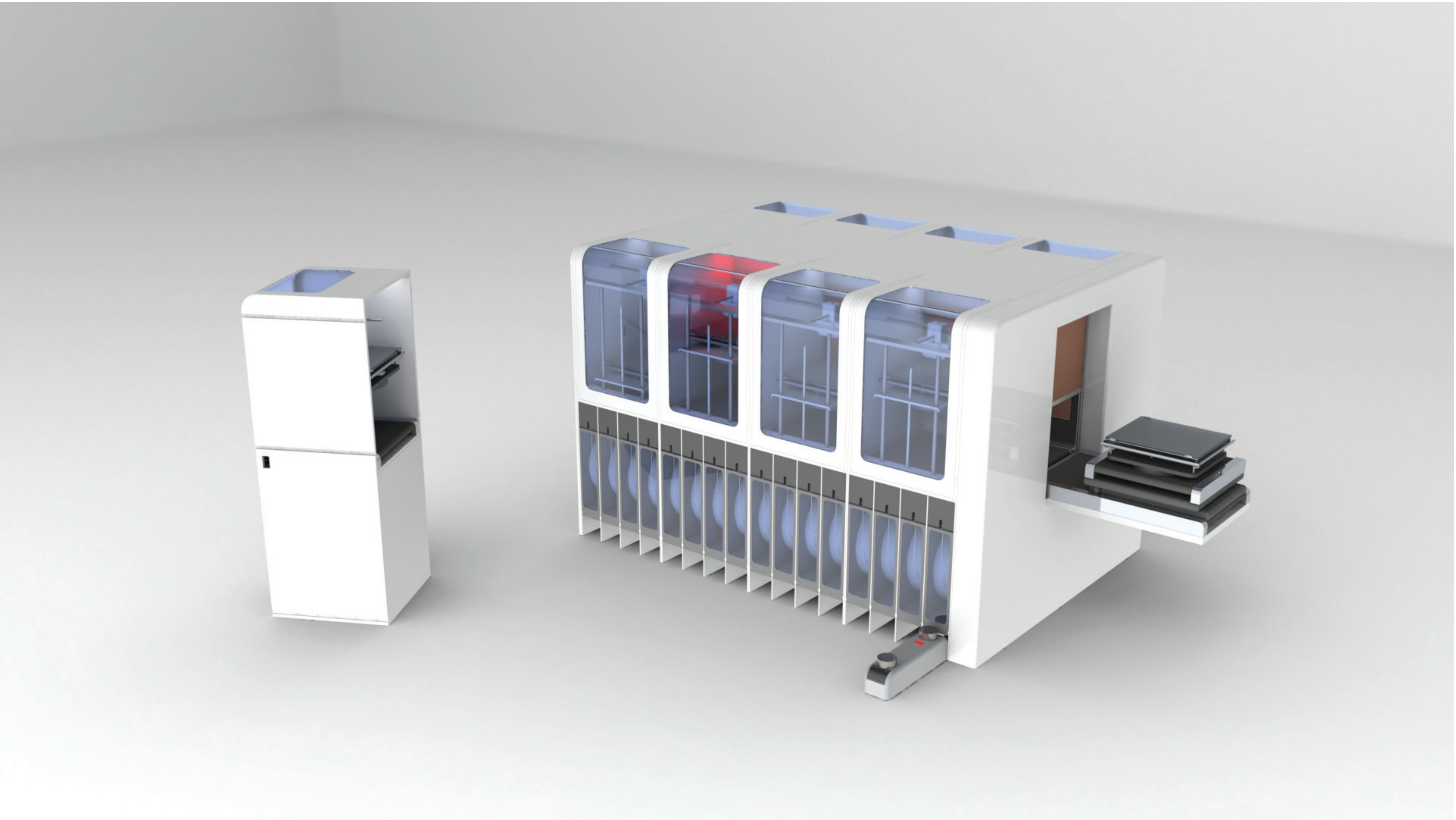


Figure 5.38 Printer malfunction

If a printer stops working and cannot be repaired immediately (figure 5.38), it is possible to pull that printer out of the line and replace it with a new one to keep up-time high (figure 5.39). If that printer was in the middle of a print that print is paused. When a printing slot becomes available the print (if the print itself has not failed) can be resumed by that printer.

The broken printer can then be repaired off-site and does not have to remain in the hub.

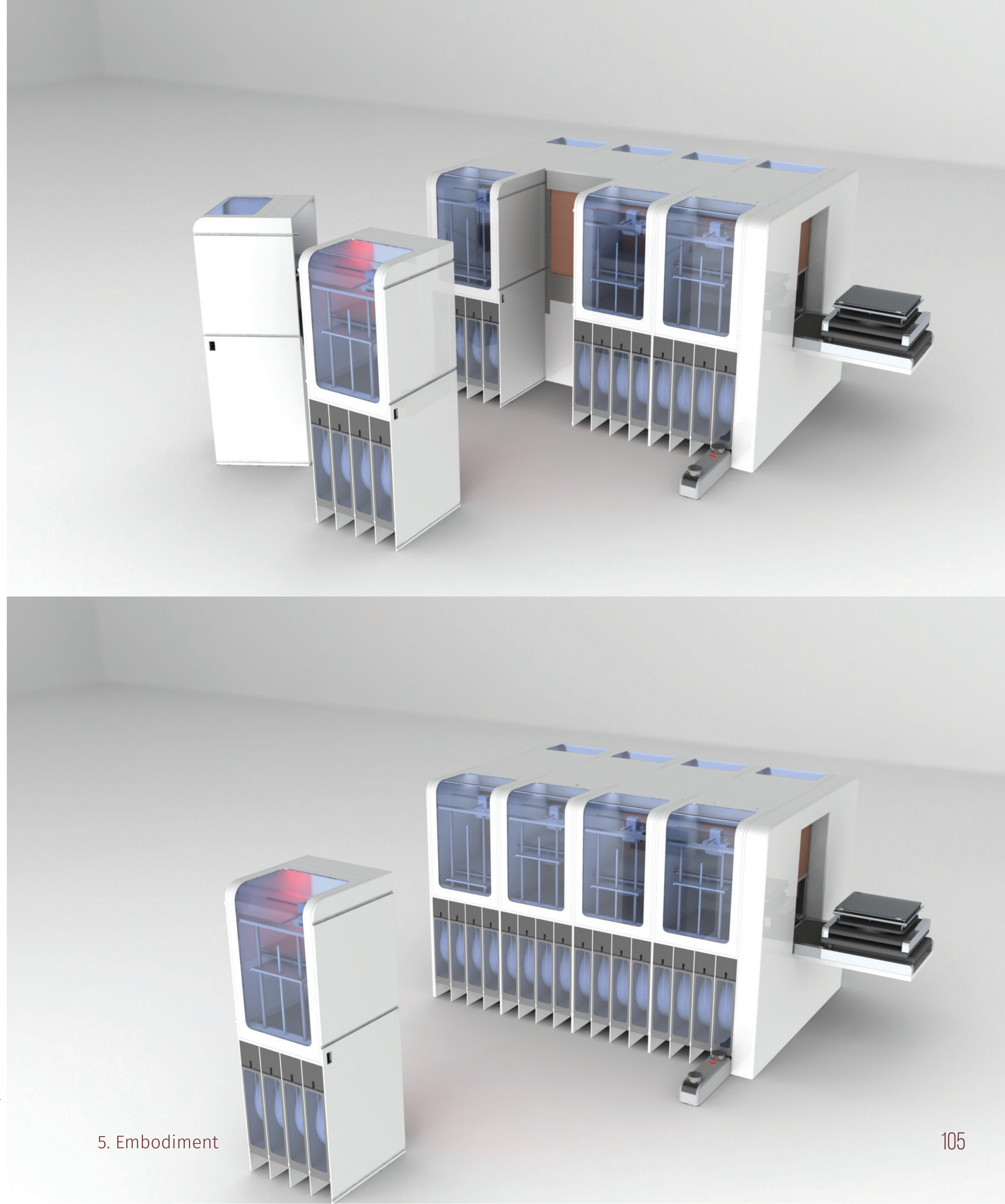


Figure 5.39 Replacing a broken printer

5.3.3 Carrier

The renders in this chapter (figure 5.40) display how a carrier enters a printing hub. The carrier approaches the printer once a printing unit is free (1). The carrier is placed precisely on the center of the "carrier carrier" (2), the RFID tag is read and the curtains of both the entrance of the hub and the selected printing unit open, the Gcode is uploaded to the printer and it begins preparing the job. The carrier is rotated in the correct orientation (3). Once the carrier is rotated and the curtain is fully opened the conveyor belts move the "carrier carrier" inside the hub (4). Sensors in the "carrier carrier" and the center unit (the small red dots in the renders) send a signal when the "carrier carrier" is in the correct location to stop the conveyor belts (5). This sensor also reads if the curtain has fully opened, if this is the case the belt of the "carrier carrier" and the printing unit start to move the carrier in the printing unit (6). A microswitch, placed at the end of the conveyor in the printing unit is pressed once the carrier is in the correct location. This sends the signal to the printer that the Z-axis can be raised (7), connecting the kinematic coupling. If the kinematic coupling contacts touch correctly, a circuit is closed. This is done as a final check to make sure the kinematic coupling is engaged. When the carrier leaves the print hub, the heat bed stays heated to maintain adhesion between the print bed and the print.

For each printing unit two carriers are included. The carriers are made in such a way they can be attached to any industry 4.0 carrier (FESTO, Bosch and KPMG examples were used). Two carriers are enough per unit, as printing takes longer than other processes. It was decided that printbeds do not need to be removable from the carrier do speed up cooling down. During prototyping it was found that a loose printbed takes 228 seconds to cool down from 85 degrees Celsius, while connected to the carrier it takes 472 seconds. Looking at the timing sheets in appendix S, there is sufficient time for this to be done before returning to the printer. To prevent having another mechanism that has the potential of failing the print bed keeps the same locks as current Ultimaker printers have.

A simulation was done on the plate of the Z-axis. It was assumed that a force of 40 newton (extreme situation with safety factor of 2) was applied. The deflection was not allowed to be higher than 0.1mm, which it was in the first instance, therefore the ribs visible in the renders were added in the final version of the plate. The ribs could not be too big, as they had to fit between the heat bed and the bottom plate of the carrier, this has been considered in making the design. The simulation can be found in appendix X.

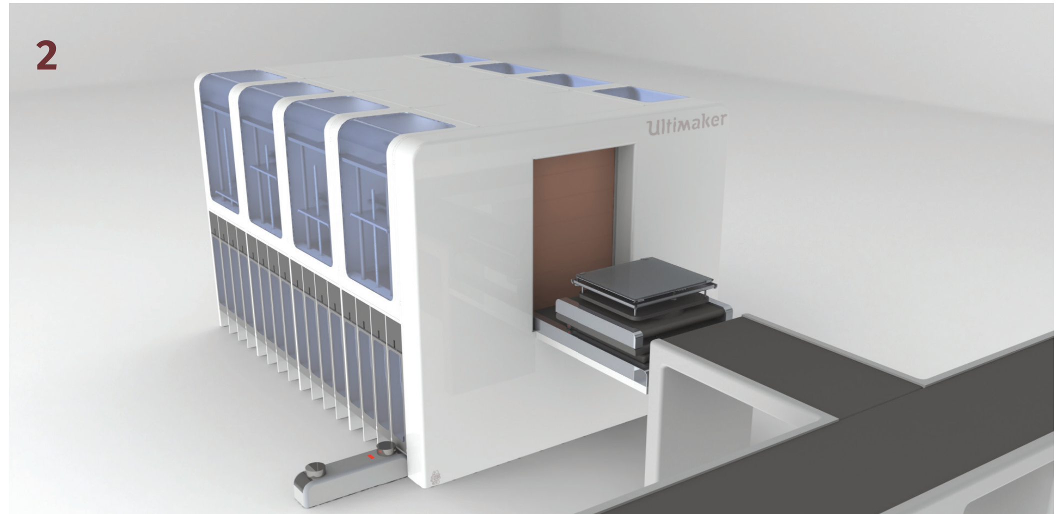
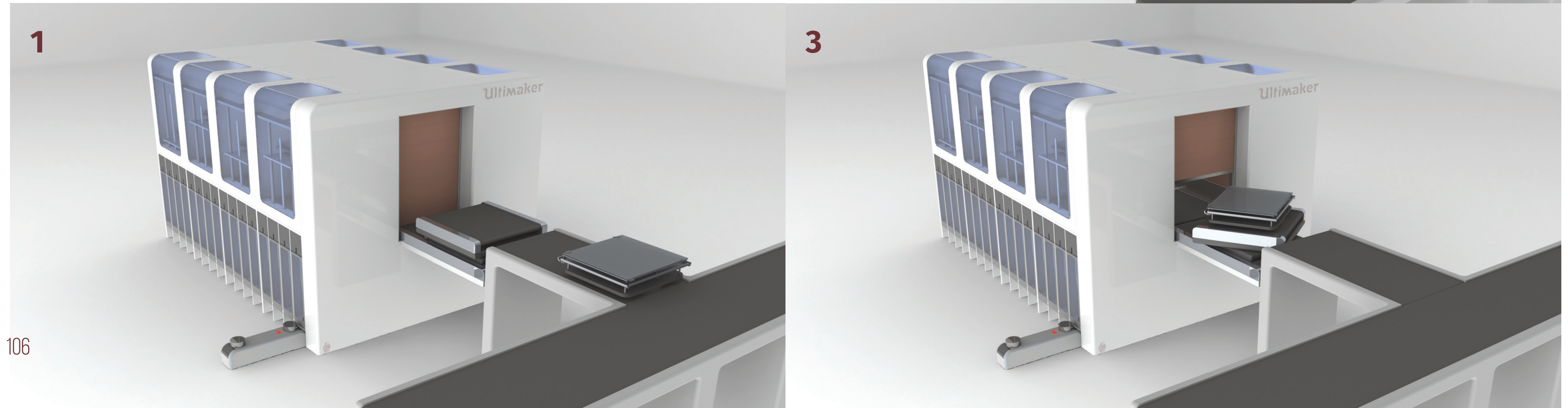
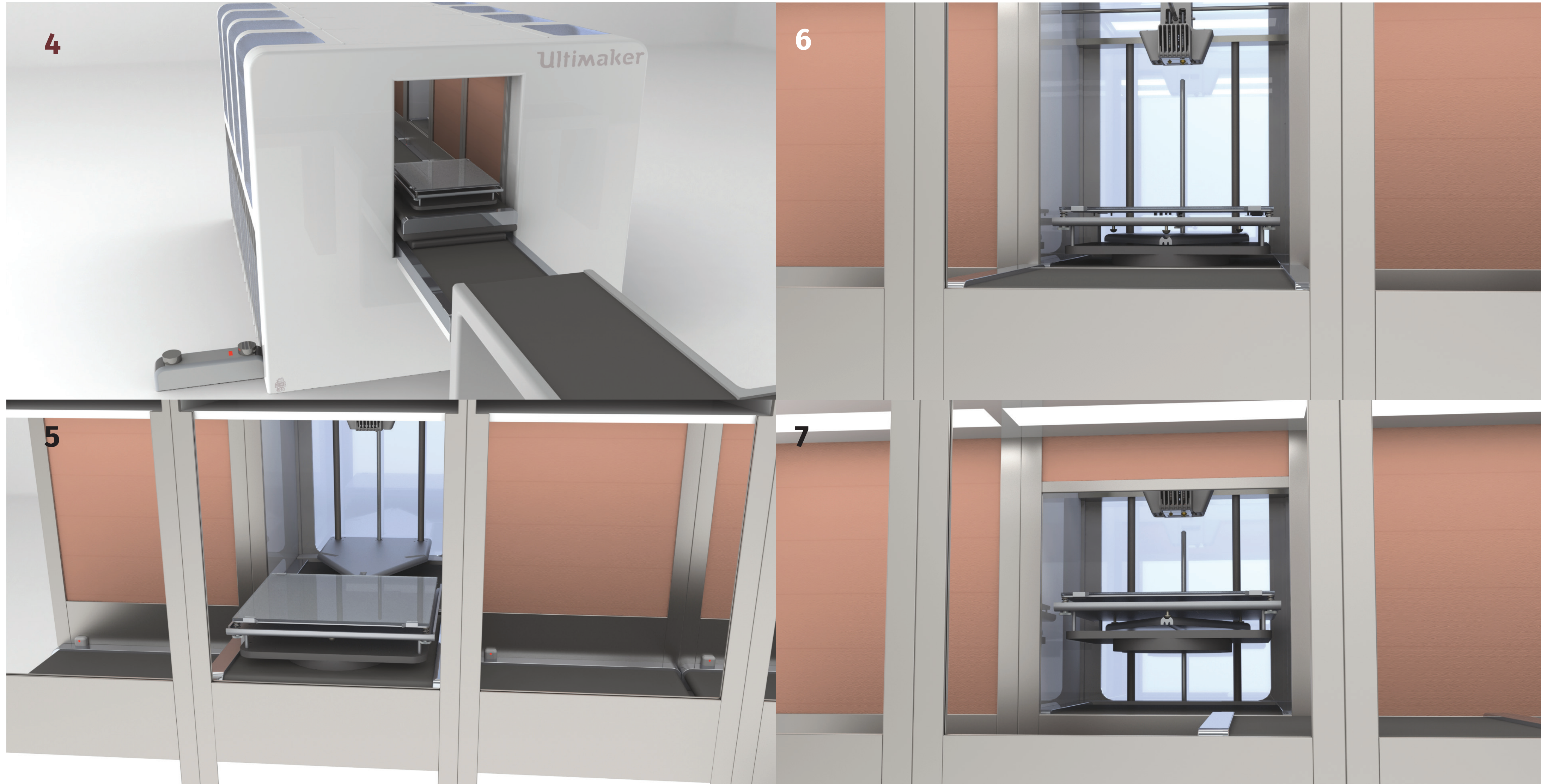


Figure 5.40 Carrier entering a printing hub





5.3.4 Redesigned curtains

The curtains have been made in such a way that they take up as little space as possible while still fully closing the entrance of the printers. Figure 5.41 show a cut-through of a hub and how the curtain falls between the conveyor belts of the "carrier carrier" and the printing unit. As long as a curtain is closed the conveyor belt in that printing unit is blocked so the carrier can not accidentally crash into the curtain.

Figure 5.42 shows a carrier entering a printing unit with the curtain opened above. The carrier does not make contact with any part of the curtain when entering the printer.

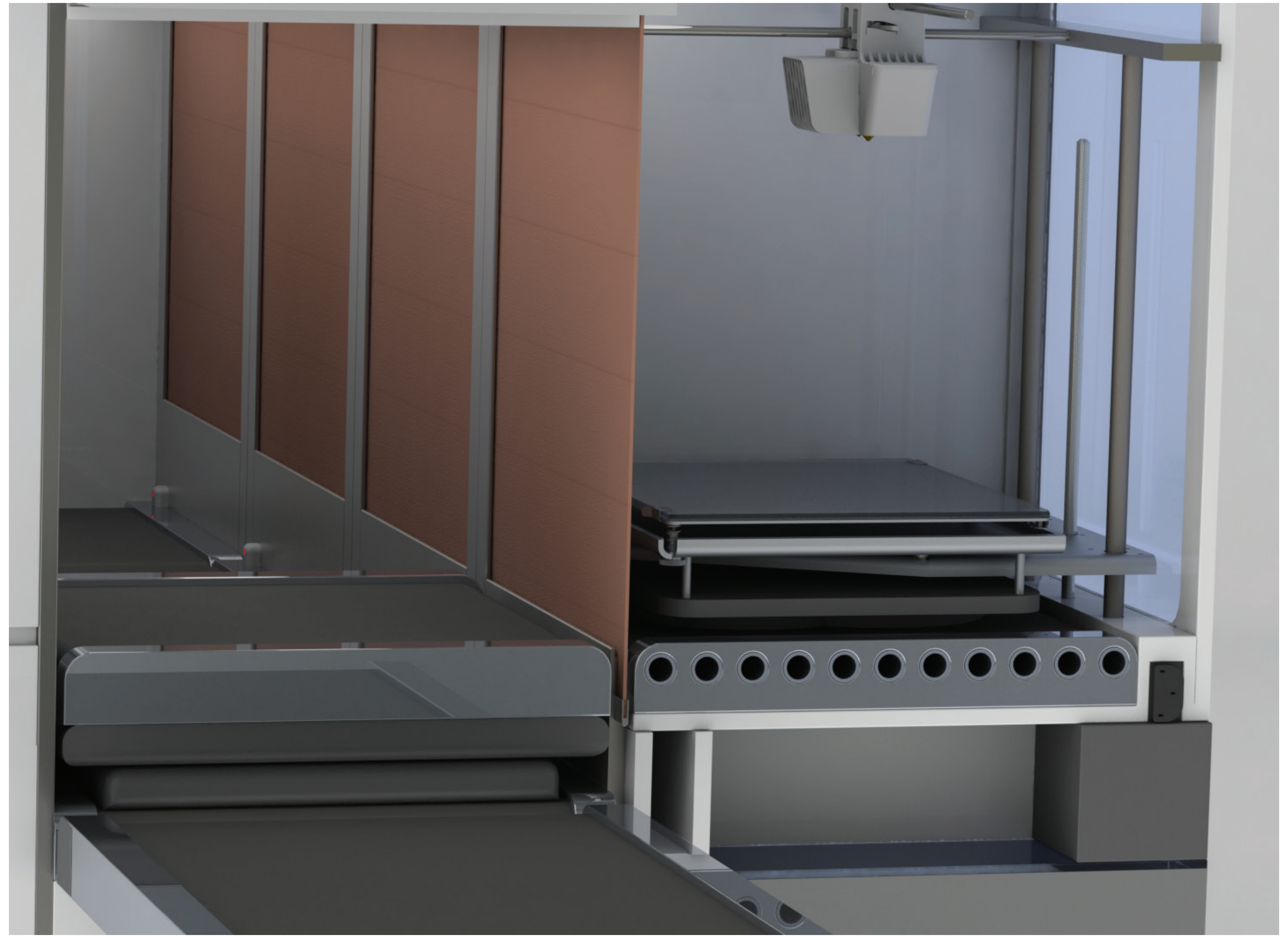


Figure 5.41 Curtain falls between belts

Figure 5.42 Carrier moves through the opening

5.4 Evaluation of requirements

This chapter looks back at the list of requirements made in chapter 2.6.2. Which requirements are met and which have not been treated. The ones that still have to be done count as recommendations towards FDM printing entering Industry 4.0.

Requirements met:

The UltiFact 4.0 offers a complete package, that is able to access the Cura material database. The underlying software does still have to be made, the concept proposed works as a framework and everything required is present. The UltiFact pushes Ultimaker to the professional product category of the competitor diagram. Up-time is maximized because everything that happens in the process that is not printing happens outside the printers. Human intervention is removed and only needed to fix failures making it automation ready. Because the foundation of the UltiFact is the Ultimaker printing platform a wide range of materials (as well as engineering materials) is still supported and newly introduced materials can be used just as with the regular Ultimaker printers. The same goes for the use of support material since the dual extruder head is still present. The system is able to produce customized products, if the software is ready to slice this, offering production flexibility.

Material parameters are controlled with the boxes from which they are printed, allowing them to be stored in an optimal environment.

Adhesion has not changed therefor, the adhesion during printing is still good and prints are released after cooling down.

The layer thickness range and minimum wall thickness are unchanged and therefor suffices to the requirement. The printing units are equipped with an enclosed heated chamber for controlled printing parameters. The building envelope is 215x215x200.

The prints leave the printer without human interference.

One of the key features is the fact that multiple printing units can be combined. This way multiple extruders are combined, increasing production. Different prints can be processed without the need to change tooling. Freedom of complexity has not been changed and is therefore maintained. The system is still flexible so upgrades and updates can still be added.

The physical process is fully monitored, creating a digital twin of the printers and the products printed. The interaction between operators and machine are made intuitively. Operators are assisted in the process.

The machine is capable of decision making when necessary and can be integrated in end to end digital production lines. Mechanical issues are identified and response is accordingly. Communication with other machines mainly goes through the central factory hub and RFID chips. The data gathered is stored in big data system, analyses are made to identify issues. All information on the system is available for operators.

Requirements that have not been included (Recommendations)

Must have the option to monitor the process autonomously. Autonomous monitoring can and should be added, it was however not included in the UltiFact yet as it did not fit the scope of the project, the same goes for the requirements on detecting errors which must be included if the Ultifact goes to the market.

The automation of order preparation did not fit the scope either as it happens before the part where the workflow of the UltiFact starts. Part removal happens outside the printer in a separate station, just as bed preparation and post processing

Waiver of liability for copyright infringement and liability for defective/unsafe prints must be included as well but have not been done during the project.

The way data is exactly transferred has not yet been defined and is key for the concept to work.

The Ultifact 4.0 has to be precisely calibrated, since the carriers have to placed at the right place in the printer unit. Meaning setup has to be done by a professional before the system can be operated by the factory.

6. CONCLUSION

"Extending the capabilities of FDM printing to Industry 4.0 standard. "

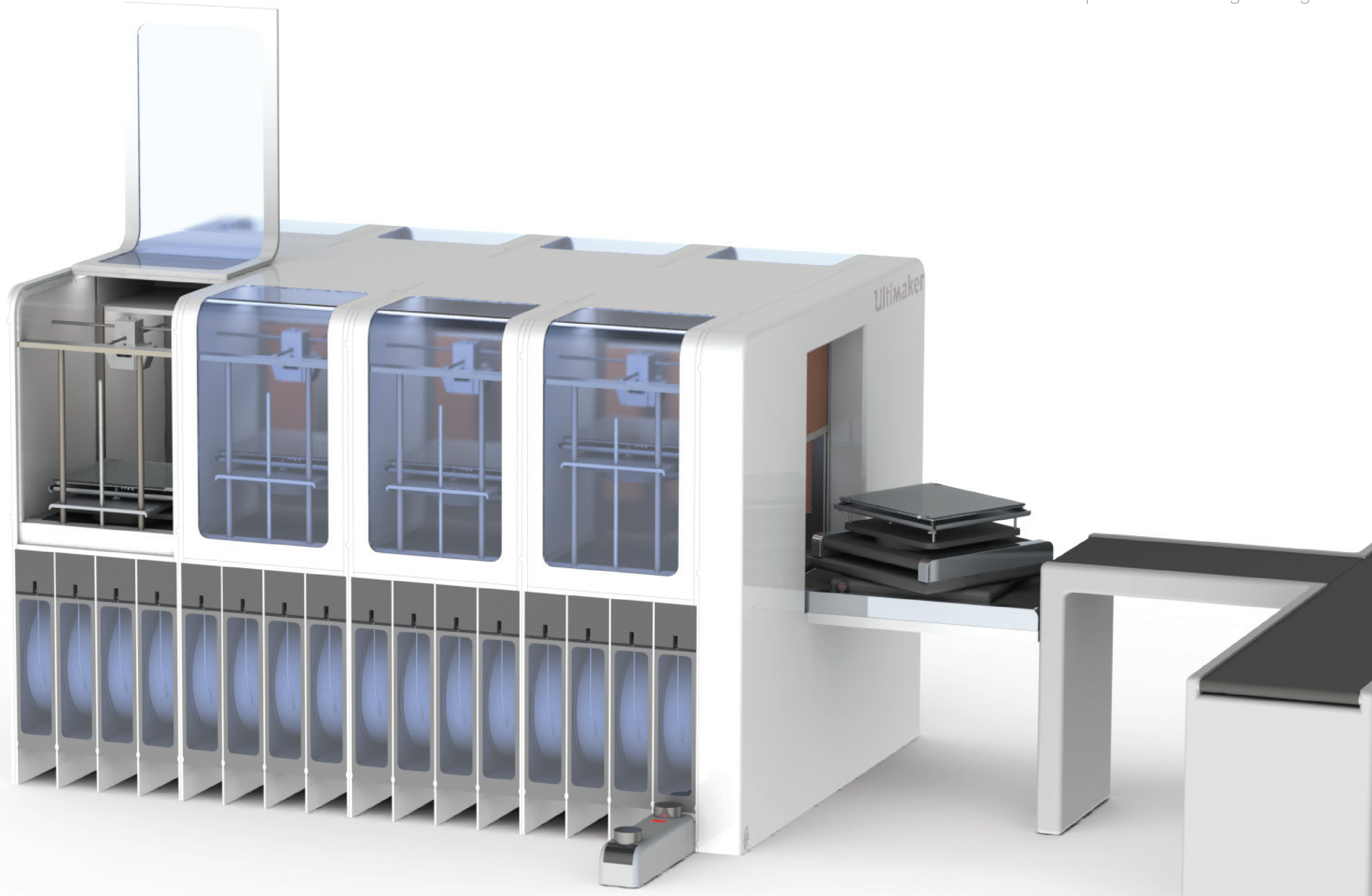
At the end of the analysis a list of requirements was proposed for FDM printing in industry 4.0. This list was used as a base for the ideation chapter. The ideation lead to two concepts which were developed and tested. For both concepts timing sheets were made, the sheets visualized that a system with carrier has the potential to maximize up-time of printers.

The research on the carrier system has proven that kinematic coupling can be used to couple the printbed to a printer. This allows for the carrier system to operate with FDM printing, making it possible to connect FDM printers with a factory 4.0 production line. To control printing parameters printing has to happen in a fully enclosed space. The research on heat curtains has led to a design of a rolling curtain that works at keeping a stable temperature inside the printing unit. A conveyor belt was used to test if the kinematic coupling works while not being placed by hand. Some guidance is needed, in the form of a bumper to stop the carrier at the correct place. The kinematic coupling works if when placed by a conveyor belt

The features of the UltiFact are capable of satisfying (almost all) the requirements defined during the analysis and therefore allow the use of FDM printing in industry 4.0.

With the concept design presented in this report the capabilities of Ultimaker printers have been extended towards Industry 4.0. There are digital solutions required to fully reach industry 4.0 that have not been included in this concept yet (like autonomous monitoring of prints).

The interconnected factory can implement the UltiFact within the production line. Allowing for a medium sized production capacity that is capable of fabricating end-use product in a flexible manner.



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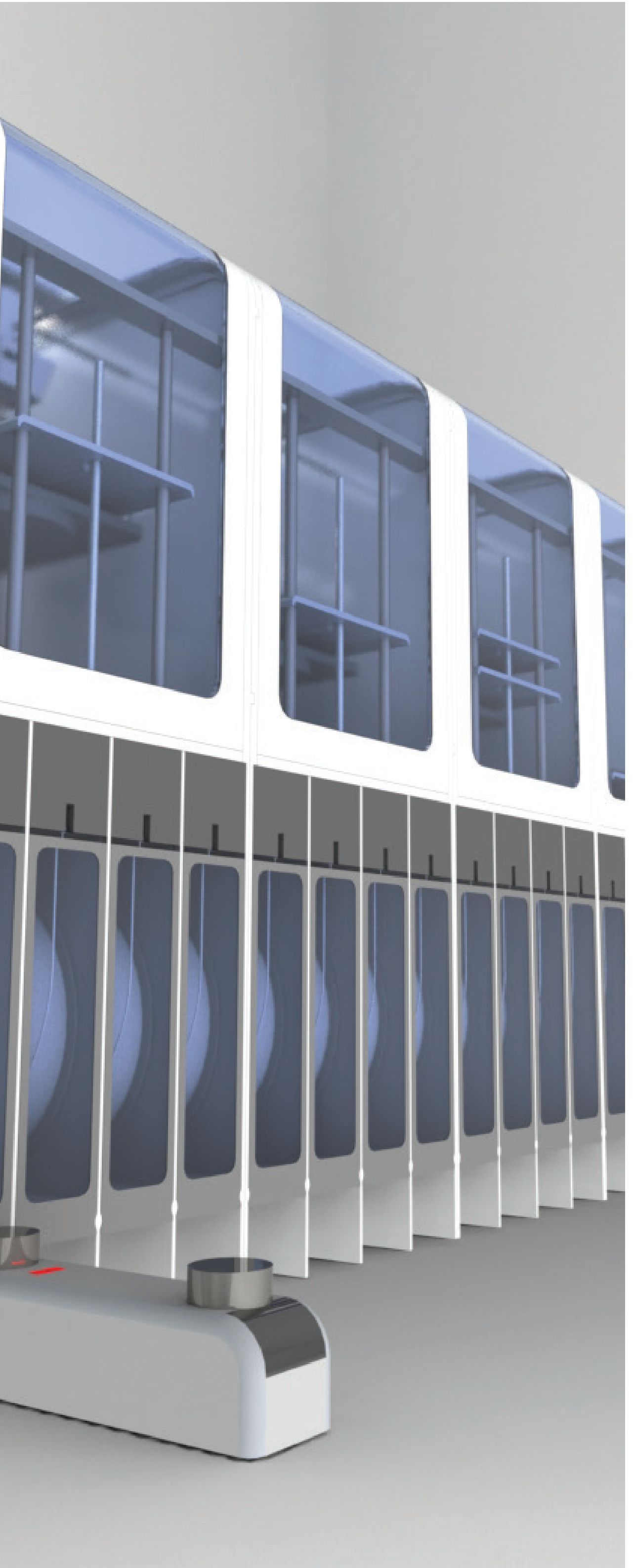
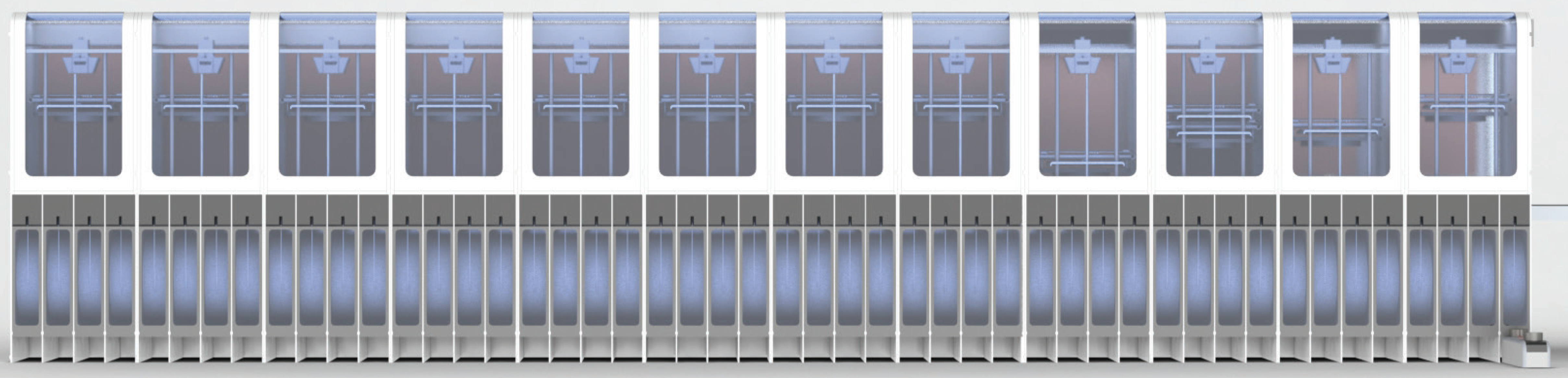


APPENDIX

A. Stakeholders 126
B. Materials 130
C. Surfaces 134
D. Sensors 138
E. Input from experts 146
F. First layer sensors 160
G. Calculations of hourly print costs 162
H. Digitization, digitalization and digital transformation 164
I. Companies implementing industry 4.0 166
J. DEPEST 168
K. List of requirements 176
L. AM Standards 180
M. UM S5 Maintenance 182
N. Design directions 190
O. Creative Facilitation session 192
P. First possible solutions 196
Q. How-to's 198
R. Grading sheets 202
S. Timing sheets 206
T. Arduino temperature sensor code 206
U. Results heat curtains 208
V. Assembly kinematic coupling 214
W. Kinematic coupling precision measurements 218
X. Simulation Z-axis plate 220



APPENDIX A

Stakeholders/fields of use

Where is 3D printing used?

- Aerospace
  - Validate designs
    - 3D printing allows for easy testing and validation of designs. This way The concept can quickly be refined and mistakes eliminated
  - Demo real-life models
    - With physical models market potential can be tested and allows for meaningful discussions with key stakeholders.
  - Complex geometries
    - It's now possible to 3D print highly customized, complex and unique models. There's no need to worry about tooling and lead-times.
  - The lighter the better
    - In a matter of hours, sometimes minutes, you can cheaply prototype airplane parts to test lighter designs before going into production.
- Architecture
- Art
- Automotive
  - Design validation
    - Validate the manufacturability of the design at early stages by printing the actual part. New iterations can be easily made in-house in a few hours, with no cost penalties.
  - Fit testing
    - With 3D printing, companies like Eventuri are able to quickly create prototypes and perform functional and fit testing before developing the final carbon fiber parts.
  - Functional prototypes
    - 3D printing custom functional prototypes in-house allows for faster and more efficient production process, from design and testing, through to production and post-processing.
  - Tools, jigs and fixtures
    - 3D printing enabled Volkswagen Autoeuropa to test construction and assembly tools, reducing their development times by 95% and achieving a 91% cost reduction.
- Engineering
  - Rapid prototyping and manufacturing
    - From model to final component in just two weeks. Normally this part would've taken 16. 3D printing is revolutionizing the manufacturing process.
  - Engineer complex geometries with ease
    - Prototyping on an Ultimaker allows you to realize your vision at low cost, refining ideas before going into production.
- Fablabs
- Fashion
  - Perfected design
    - With 3D scanning, it's possible to create fashion that fits anyone perfectly. Shoes, glasses and clothing that adapt to you.
  - Precision fashion
    - Within hours, a design is tactile
  - Material options
- Humanitarian aid
  - 100% Recycled filament
  - Helping the visually impaired
    - 3D printed instruments can be printed locally to find eye problems in its early stages – while they're still able to be saved.
  - Open source prosthetics
    - A global network of volunteers uses 3D printing to literally give people a 'helping hand'.
  - Recycling plastic waste
- Jewelry
  - 3D prints for fit testing
    - The perfect fit is essential. With a 3D printer jewelers can get customer feedback instantly, then try different sizes.
  - 3D printed beauty
    - Jewelry realized with 3D printing takes on a whole new dimension.
  - Cast the final product
    - 3D printing can be used alongside traditional craftsmanship to save time and open up new possibilities, like using it to cast the product.
- Manufacturing
  - 3D printed part to metal part
    - Siemens now turns a 3D printed component into a final product cast in 316 grade stainless steel in 1-2 weeks instead of 16, saving time and costs.
  - Improving assembly lines
    - 3D printed manufacturing aids are helping to increase the efficiency of assembly lines. It's fast, cheap and everything is done in-house.
  - Bridge manufacturing
    - 3D printing is used to produce small batches of products significantly reducing the time to market while focusing on innovation.
  - Fresh business models
    - As 3D printing grows it becomes more and more accessible.
- Medicine
  - Pre-plan surgeries to improve outcomes
  - Clear communication with patients
  - Quickly validate designs
  - Real-life anatomical models
- Product design
  - Streamlined product design
    - With 3D printing, manufacturing timelines are shrinking. Design to product timings are shorter, allowing for faster more refined innovations.
  - Real models
    - With 3D printing it's possible to get a real-life model in a few hours instead of weeks. So a fit test can be done and direct feedback from customers can be acquired.
  - Proof before production
    - The form, function and manufacturing

APPENDIX A

viability can be validated early in the process.

- Fresh business models
  - As 3D printing grows it becomes more and more accessible. Once everyone's using it, the need for quality models will greatly increase.
- Research
- Open flexibility
- Team Fast's future fuel
- 3D bioprinting breakthrough
- Primary education
- Secondary education
- Universities
- DIY, hobbies and home (makers)
- Resellers
- Transport
- Filament producers
- Plastics industry
- Management

APPENDIX B

Materials

1. PLA

The most popular (3d Printing. 2018) desktop 3D printing material. PLA is easy to print with and comes in a wide range of colors. The extruder temperature for PLA is recommended to be between 190 and 230 degrees Celsius with an optional print bed temperature between 25 and 60°C (Polymaker. 2018). PLA is biodegradable and derived from renewable resources (e.g. Corn starch).

2. ABS

ABS (Acrylonitrile Butadiene Styrene) is a petroleum-based polymer (Rogers, T. 2015). ABS filament is also one of the more commonly used 3D printing materials, it is known for its ductility and high temperature resistance. For post processing it is possible to finish with Acetone, giving it a smooth and shiny surface finish. Extrusion temperature is between 230 and 255°C, with a printbed temperature between 80 and 100 °C (Innofil3D. 2018). It is recommended to print ABS in an enclosed area, as it is prone to warping (123D. 2018) and there is a potentially high fume emission (3dhubs. 2017). ABS is sensitive to UV radiation.

3. PETG (CPE at Ultimaker)

PETG is becoming more standard for 3d printing as it combines the ease of use of PLA with the strength and durability of ABS (3Dprinting. 2019). One of its strengths is impact resistance. PETG filament has been FDA approved (Scott, C. 2016) meaning the material is food safe, there are however restrictions for this as the process is important as well and residue of other materials might contaminate the plastic. PETG is Printed with an extruder temperature between 230 and 240°C and a print bed between 70 and 80°C (Polymaker. 2018).

4. PA

PA (Nylon) is strong, rigid and flexible. It is sensitive to moisture making it difficult to print and store (Matterhackers. 2017). Nylon filament has a high inter-layer adhesion making it suitable for functional parts, for example connectors and hinges. An extruder temperature between 220 and 245°C is recommended with a print bed temperature between 80 and 120°C it is also recommended to have a room temperature between 40 and 70°C (Nexeo Novamid, 2018).

5. TPU

TPU (Thermoplastic Polyurethane) is a flexible material, TPU is used in consumer products like phone cases, footwear and watch bands (Grames, E. 2018). TPU has a decent level of chemical resistance. It is oil & grease resistant and tough against abrasions. It is recommended for extrusion between 225 and 235°C and with a print bed temperature between room temperature and 40°C (NinjaFlex. 2018).

6. PC

PC (Polycarbonate) is a filament that offers a high fracture toughness which is unobtainable with other filaments of comparable stiffness (Polymaker. 2019). It is a tough and durable 3D printing material while also resistant to temperature of just over 110°C (Kondo, H. 2018). PC is a good choice for end use applications. Extrusion temperature is recommended between 250 and 270°C with a print bed temperature between 100 and 130°C (Polymaker. 2018).

7. HIPS

HIPS (high impact polystyrene) is often used as a support material for ABS as it bonds well and prints under the same circumstances and can be dissolved using Limonene. (Grams, E. 2018). An extrusion temperature between 230 and 240°C with a print bed temperature between 80 and 115°C (MG Chemicals. 2019).

8. ASA

ASA (Acrylonitrile Styrene Acrylate) has high strength and resilience. It is weather resistant, and therefore applicable in outdoor appliances (Mashambanhaka. 2018). Extrusion temperature is recommended between 250 and 270°C with a print bed temperature between 80 and 90°C (Formfutura. 2018).

9. PP

PP (Polypropylene) is a strong and ductile material it can be elongated further without breaking as compared to other 3D printing materials. (Leapfrog. 2018) Extrusion temperature is recommended around 220°C with a print bed temperature around 100°C (Verbatim. 2019).

10. PEEK

PEEK is a high strength, chemically resistant and impact resistant material that requires higher print temperatures than most other material. It is an industrial 3D printing material that can substitute certain metals in terms of durability and strength. PEEK filament has many applications including those in aerospace, oil and the packaging industries. Learn more about PEEK in our PEEK printing guide. Extrusion temperature is recommended between 375 and 410°C with a print bed temperature between 130 and 145°C in a room heated between 70 and 150°C (3DXTech. 2019).

APPENDIX B

11. ULTEM (PEI)

ULTEM is a subclass of Polyetherimide (PEI) materials. ULTEM gains strength in combination with glass fiber reinforcement, making it one of the strongest 3D printing materials available. ULTEM filament has been used to replace metal parts, Boeing and Airbus are producing airplane parts with Ultem (Ku, C. 2015). Extrusion temperature is recommended between 370 and 390°C with a print bed temperature between 120 and 160°C in a room heated between 70 and 150°C (3DXTech. 2019).

As ULTEM is often mentioned as one of the most important and strongest industrial grade FDM printing materials some research was done into it, an overview of how it can be printed:

- Extruder Temp: 370 - 390°C
- Bed Temp: 120 - 160°C
- Bed Preparation: Specialized tape is the ideal build surface
- Print Speed: Print speeds of 20-30mm/s (starting point), faster as results dictate
- Enclosure Temp: Ultem prints best in a warm to hot build environment (70-150°C)
- Parts printed with Ultem can be annealed in a hot-air oven to reduce any printed-in stresses and increase their mechanical properties

12. PVA (Soluble)

Polyvinyl Alcohol (PVA) is a water-soluble 3D printing material which is used as support. It essential in the realization of complex designs where support removal can damage the product. Due to its water solubility, PVA filament absorbs moisture meaning special storage conditions are required (Greguric, L. 2018). Extrusion temperature is recommended between 215 and 225°C with a print bed temperature between 25 and 60°C (Polymaker. 2018).

APPENDIX C

C

Printing surfaces

The data presented below is gathered by interviewing experts (Ultimaker, Prusa and 123D) combined with information presented by companies selling the build surfaces. There is not 1 best build surface as this is dependable of the application and material used, therefor the surfaces are presented in no specific order. The list shows the advantages and disadvantages of the surfaces and mentions the materials it is specified for, so if a material is not mentioned it does not mean the combination does not work, it is not recommended.

Painters tape

- Advantages
  - Cheap and accessible
  - Easy to apply
  - Prints can be removed easily
- Disadvantages
  - Low durability (needs refreshing after 3 prints)
  - Low surface quality
- Materials
  - PLA
  - PETG
  - TPU
- Further

Used to be the most popular bed adhesion until companies started making more durable and less labor intensive (for the user) printing surfaces. The painters tape works due to a polymer coating to which the prints adhere.

Kapton tape

- Advantages
  - More durable than painters tape
  - Good surface quality
- Disadvantages
  - Hard to apply well
  - Calibration needed after application
- Materials
  - ABS
- Further

Kapton tape has a higher temperature tolerance than painters' tape. making it suitable for printing on a heated plate, it helps against warping of ABS prints, a well calibrated printer is needed for the tape to be useful.

(Heated) Glass

- Advantages
  - Good surface quality
  - Consistently flat
  - Very durable (can last 1000+ prints if maintained well)
  - Prints are (relatively) easily removed
- Disadvantages
  - Surface needs treatment to keep adhesion (alcohol, hairspray or glue stick are common)
  - Can break
- Materials
  - PLA
  - PETG
  - General purpose
- Further

(Borosilicate) Glass can be produces extremely flat, which is critical for a decent first layer, it was the first lasting solution for a combination with a heated build plate.

ABS Glue

- Advantages
  - Prevents ABS prints from warping
- Disadvantages
  - Labor intensive to produce, right ratio required to work
  - Needs to be reapplied after 3 prints
- Materials
  - ABS
- Further

A mixture of ABS and acetone, used as a coating to get better adhesion, ABS sticks to ABS well, this is used in industrial applications as well for 3d printing (Robo3D. 2018).

Glue stick

- Advantages
  - Can be used for each material
  - Easy to apply
  - Accessible
- Disadvantages
  - Leaves residue on printbed, hard to clean
  - Needs to be reapplied after 3 prints
- Materials
  - PLA, ABS, PET
- Further

A glue stick is also one of the more common adhesion methods. It is sometimes also used to prevent a print from sticking too much (for example to PEI) and damaging the surface.

APPENDIX C

PEI Sheet

- Advantages
  - Good surface quality
  - Very durable (can last 1000+ prints if maintained well)
  - Good adhesion with materials
- Disadvantages
  - Marks can be left on the surface (dents/scratches)
- Materials
  - General purpose
- Further

Polyetherimide (PEI) is increasing in popularity. It can be sanded when the material loses its adhesive properties to extend the lifetime.

Plastic sheets (Buildtak)

- Advantages
  - Very durable (can last 1000+ prints if maintained well)
  - Strong adhesion with materials
- Disadvantages
  - Adhesion can be too strong
  - Can be damaged by too strong adhesion
- Materials
  - Nylon (on Garolite, material used for circuitboards)

Flexible plates

- Advantages
  - Removable from the printer
  - Prints can be released by flexing the plate
  - Can be used as long as the printer
- Disadvantages
  - More expensive than other surfaces
- Materials
  - General purpose
- Further

Most new desktop FDM printers come equipped with flexible plates. It is a spring steel sheet that is covered with another surface (PEI or Buildtak for instance). It is attached to a headbed by using magnets so it can also easily be removed and placed back.

Magigoo

- Advantages
  - Easily applied
  - Cheap
  - Easier to clean than glue sticks
  - Lasts longer than glue sticks (needs refreshing after about 10 prints)
- Disadvantages
  - More expensive than regular glue sticks
- Materials
  - General purpose

Wolfbite

- Advantages
  - Glues firm to the bed as long as it is hot
  - Print is not attached at all at room temperature
- Disadvantages
  - Too much can remove chunks from the bed
- Materials
  - ABS

APPENDIX D

Types of Sensors

High chance of being usable
Some chance of being usable
Low chance of being usable
Acoustic, sound and vibration

Geophone

- A geophone is a device that converts ground movement (velocity) into voltage, which may be recorded at a recording station. The deviation of this measured voltage from the base line is called the seismic response and is analyzed for structure of the earth.
- Hydrophone
- Lace Sensor a guitar pickup
- Microphone
- A transducer that converts sound into an electrical signal.

Automotive, transportation

- Air flow meter
- Air–fuel ratio meter
- Blind spot monitor
- Crankshaft position sensor, A crank sensor is an electronic device used in an internal combustion engine to monitor the position or rotational speed of the crankshaft.
- Curb feeler, used to warn driver of curbs
- Defect detector, used on railroads to detect axle and signal problems in passing trains
- Engine coolant temperature sensor, or ECT sensor, used to measure the engine temperature
- Hall effect sensor, used to time the speed of wheels and shafts, for example speedometer
- Knock sensor, used to detect detonation in internal combustion engines
- MAP sensor, Manifold Absolute Pressure, used in regulating fuel metering.
- Mass flow sensor, or mass airflow (MAF) sensor, used to tell the ECU the mass of air entering the engine
- Oxygen sensor, used to monitor the amount of oxygen in the exhaust
- Parking sensors, used to alert the driver of unseen obstacles during parking maneuvers
- Radar gun, used to detect the speed of other objects
- Speedometer, used measure the instantaneous speed of a land vehicle
- Speed sensor, used to detect the speed of an object
- Throttle position sensor, used to monitor the position of the throttle in an internal combustion engine
- Tire-pressure monitoring sensor, used to monitor the air pressure inside the tires
- Torque sensor, or torque transducer or torquemeter measures torque (twisting force) on a rotating system.
- Transmission fluid temperature sensor, used to measure the temperature of the transmission fluid
- Turbine speed sensor (TSS), or input speed sensor (ISS), used to measure the rotational speed of the input shaft or torque converter
- Variable reluctance sensor, used to measure position and speed of moving metal components
- Vehicle speed sensor (VSS), used to measure the speed of the vehicle
- Water sensor or water-in-fuel sensor, used to indicate the presence of water in fuel
- Wheel speed sensor, used for reading the speed of a vehicle's wheel rotation

Chemical

- Breathalyzer
- Carbon dioxide sensor
- Carbon monoxide detector
- Catalytic bead sensor
- Chemical field-effect transistor
- Chemiresistor
- Electrochemical gas sensor
- Electronic nose
- Electrolyte–insulator–semiconductor sensor
- Fluorescent chloride sensors
- Holographic sensor
- Hydrocarbon dew point analyzer
- Hydrogen sensor
- Hydrogen sulfide sensor
- Infrared point sensor
- Ion-selective electrode
- Nondispersive infrared sensor
- Microwave chemistry sensor
- Nitrogen oxide sensor
- Olfactometer
- Optode
- Oxygen sensor
- Ozone monitor
- Pellistor
- pH glass electrode
- Potentiometric sensor
- Redox electrode
- Smoke detector
- Zinc oxide nanorod sensor

Electric current, electric potential, magnetic, radio

- Current sensor
- Daly detector
- Electroscope
- Electron multiplier
- Faraday cup
- Galvanometer
- Hall effect sensor
- Hall probe
- Magnetic anomaly detector
- Magnetometer
- Magnetoresistance
- MEMS magnetic field sensor
- Metal detector

APPENDIX D

- Planar Hall sensor
- Radio direction finder
- Voltage detector

Flow, fluid velocity

- Air flow meter
- Anemometer
- Flow sensor
- Gas meter
- Mass flow sensor
- Water meter

Ionizing, radiation, subatomic particles

- Cloud chamber
- Geiger counter
- Neutron detection
- Scintillation counter

Navigation instruments

- Air speed indicator
- Altimeter
- Attitude indicator
- Depth gauge
- Fluxgate compass
- Gyroscope
- Inertial navigation system
- Inertial reference unit
- Magnetic compass
- MHD sensor
- Ring laser gyroscope
- Turn coordinator
- TiaLinx sensor
- Variometer
- Vibrating structure gyroscope
- Yaw rate sensor

Position, angle, displacement, distance, speed, acceleration

- Accelerometer
- Accelerometers can be used to measure vehicle acceleration. Accelerometers can be used to measure vibration on cars, machines, buildings, process control systems and safety installations. They can also be used to measure seismic activity, inclination, machine vibration, dynamic distance and speed with or without the influence of gravity. Applications for accelerometers that measure gravity, wherein an accelerometer is specifically configured for use in gravimetry, are called gravimeters. Notebook computers equipped with accelerometers can contribute to the Quake-Catcher Network (QCN), a BOINC project aimed at scientific research of earthquakes
- Accelerometers are also used for machinery health monitoring to report the vibration and its changes in time of shafts at the bearings of rotating equipment such as turbines, pumps, fans, rollers, compressors, or bearing fault which, if not attended to promptly, can lead to costly repairs. Accelerometer vibration data allows the user to monitor machines and detect these faults before the rotating equipment fails completely.
- Auxanometer
- Capacitive displacement sensor
- Capacitive sensing
- Flex sensor
- Free fall sensor
- Gravimeter
- Gyroscopic sensor
- Impact sensor
- Inclinometer
- Integrated circuit piezoelectric sensor
- Laser rangefinder
- Laser surface velocimeter
- A laser surface velocimeter (LSV) is a non-contact optical speed sensor measuring velocity and length on moving surfaces. Laser surface velocimeters use the laser Doppler principle to evaluate the laser light scattered back from a moving object. They are widely used for process and quality control in industrial production processes.
- LIDAR
- Linear encoder
- Linear variable differential transformer (LVDT)
- Liquid capacitive inclinometers
- Odometer
- Photoelectric sensor
- Piezocapacitive sensor
- Piezoelectric accelerometer
- Position sensor
- Position sensitive device
- Rate sensor
- Rotary encoder
- Rotary variable differential transformer
- Selsyn
- Shock detector
- Shock data logger
- Stretch sensor
- Tilt sensor
- Tachometer
- Ultrasonic thickness gauge
- Variable reluctance sensor
- Velocity receiver

Optical, light, imaging, photon

- Charge-coupled device
- CMOS sensor
- Colorimeter
- Contact image sensor
- Electro-optical sensor
- Flame detector
- Infra-red sensor
- Kinetic inductance detector
- LED as light sensor
- Light-addressable potentiometric sensor
- Nichols radiometer
- Fiber optic sensors
- Optical position sensor

APPENDIX D

- Thermopile laser sensors
- Photodetector
- Photodiode
- Photomultiplier tubes
- Phototransistor
- Photoelectric sensor
- Photoionization detector
- Photomultiplier
- Photoresistor
- Photoswitch
- Phototube
- Scintillometer
- Shack-Hartmann
- Single-photon avalanche diode
- Superconducting nanowire single-photon detector
- Transition edge sensor
- Visible light photon counter
- Wavefront sensor

Pressure

- Barograph
- Barometer
- Boost gauge
- Bourdon gauge
- Hot filament ionization gauge
- Ionization gauge
- McLeod gauge
- Oscillating U-tube
- Permanent Downhole Gauge
- Piezometer
- Pirani gauge
- Pressure sensor
- Pressure gauge
- Tactile sensor
- Time pressure gauge

Force, density, level

- Bhangmeter
- Hydrometer
- Force gauge and Force Sensor
- Level sensor
- Load cell
- Magnetic level gauge
- Nuclear density gauge
- Piezocapactive pressure sensor
- Piezoelectric sensor
- Strain gauge
- Torque sensor
- Viscometer

Thermal, heat, temperature

- Bolometer
- Bimetallic strip

- Heatbed van maken, door warmte (die nodig is bij het printen) recht laten worden, wanneer print klaar is afkoelen buigt waardoor print los schiet
- Calorimeter
- Exhaust gas temperature gauge
- Flame detection
- Gardon gauge
- Golay cell
- Heat flux sensor
- Infrared thermometer
- Microbolometer
- Microwave radiometer
- Net radiometer
- Quartz thermometer
- Resistance temperature detector
- Resistance thermometer
- Silicon bandgap temperature sensor
- Special sensor microwave/imager
- Temperature gauge
- Thermistor
- Thermocouple
- Thermometer
- Pyrometer

Proximity, Presence

- Alarm sensor
- Doppler radar
- Motion detector
- Occupancy sensor
- Proximity sensor
- Passive infrared sensor
- Reed switch
- Stud finder
- Triangulation sensor
- Touch switch
- Wired glove

Sensor technology

- Active pixel sensor
- Back-illuminated sensor
- Biochip
- Biosensor
- Capacitance probe
- Capacitance sensor
- Catadioptric sensor
- Carbon paste electrode
- Digital sensors
- Displacement receiver
- Electromechanical film
- Electro-optical sensor
- Fabry–Pérot interferometer
- Fisheries acoustics
- Image sensor
- Image sensor format
- Inductive sensor
- Intelligent sensor
- Lab-on-a-chip
- Leaf sensor
- Machine vision
- Microelectromechanical systems
- Photoelasticity
- Quantum sensor
- Radar
- Ground-penetrating radar
- Synthetic aperture radar
- Radar tracker
- Stretch sensor
- Sensor array
- Sensor fusion
- Sensor grid
- Sensor node

APPENDIX D

- Soft sensor
- Sonar
- Staring array
- Transducer
- Ultrasonic sensor
- Video sensor
- Visual sensor network
- Wheatstone bridge
- Wireless sensor network

Other sensors, sensor related properties and concepts

- Actigraphy
- Air pollution sensor
- Analog image processing
- Atomic force microscopy
- Atomic Gravitational Wave Interferometric Sensor
- Attitude control (spacecraft): Horizon sensor, Earth sensor, Sun sensor
- Catadioptric sensor
- Chemoreceptor
- Compressive sensing
- Cryogenic particle detectors
- Dew warning
- Diffusion tensor imaging
- Digital holography
- Electronic tongue
- Fine Guidance Sensor
- Flat panel detector
- Functional magnetic resonance imaging
- Glass break detector
- Heartbeat sensor
- Hyperspectral sensors
- IRIS (Biosensor), Interferometric Reflectance Imaging Sensor
- Laser beam profiler
- Littoral Airborne Sensor/Hyperspectral
- LORROS
- Millimeter wave scanner
- Magnetic resonance imaging
- Moire deflectometry
- Molecular sensor
- Nanosensor
- Nano-tetherball Sensor
- Omnidirectional camera
- Organoleptic sensors
- Optical coherence tomography
- Phase unwrapping techniques
- Polygraph Truth Detection
- Positron emission tomography
- Push broom scanner
- Quantization (signal processing)
- Range imaging
- Scanning SQUID microscope
- Single-Photon Emission Computed Tomography (SPECT)
- Smartdust
- SQUID, Superconducting quantum interference device
- SSIES, Special Sensors-Ions, Electrons, and Scintillation thermal plasma analysis package
- SSMIS, Special Sensor Microwave Imager / Sounder
- Structured-light 3D scanner
- Sun sensor, Attitude control (spacecraft)
- Superconducting nanowire single-photon detector
- Thin-film thickness monitor
- Time-of-flight camera
- TriDAR, Triangulation and LIDAR Automated Rendezvous and Docking
- Unattended Ground Sensors

APPENDIX E

Input from experts

Insights Interview Rutger Schönfeld – Maintained an UM2 print farm

Used to be a student IPD. Graduated on a project about 3D printed braces for people with artrose.

Oud-student IPD. Afgestudeerd met een 3D geprinte Brace voor mensen met artrose, eerste gedeelte erg technisch en bezig met het scannen van handen en armen om alles passend te krijgen. Het werd echter niet als prettig beschouwd door gebruikers omdat het te weinig werd gedragen. In het tweede gedeelte meer gefocust op ergonomie en dan met name op het gebied van cognitieve ergonomie. Momenteel onder andere werkend als PO1 begeleider bij industrieel ontwerpen op de TU Delft. Heeft de Ultimaker 2+ printers bij industrieel ontwerpen beheerd en bezit daardoor zeer waardevolle kennis op dit gebied. Bij het onderhoud was zijn taak de logistiek regelen met de verantwoordelijke personen hiervoor. Het plaatsen en schoonhouden van de printers, materiaal aanvullen, leren aan studenten. Dit geheeld voelde als een soort kindercrèche elke ochtend.

Elke ochtend en het liefst ook elke middag de printers controleren, schoonmaken, prints verwijderen en materiaal verwisselen.

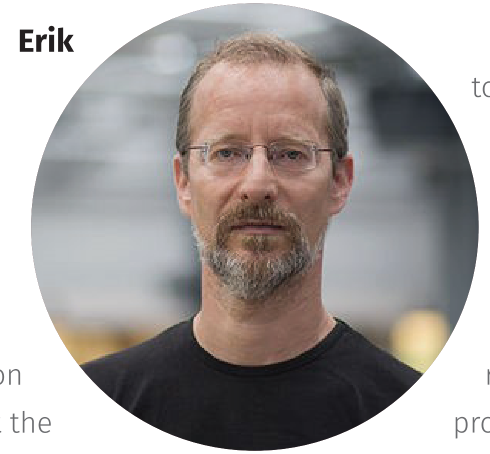
Problemen waar tegenaan werd gelopen waren dat er kieren tussen de feeder en extruder kwamen waardoor de boel ging verstoppen, dit moest dan weer schoongemaakt worden. Een feeder die zichzelf in het materiaal groef. Verstopte printkoppen waardoor de print te dun was of helemaal niet er uit kwam, heatbeds die te hoog of te laag waren. Zelf heeft hij een delta printer, deze is nog veel lastiger af te stellen en gaat snel scheef hangen.

Belangrijkste is dat de eerste laag goed geprint wordt, hier gaat het meeste fout waardoor de gehele print faalt. Dit betekent dus dat je het eerste halfuur niet weg kunt gaan van de printer, kost erg veel tijd waar je alleen maar zit te kijken en dus niet nuttig bezig bent.

De UM2+ had geen sensor die aangeeft of de rol op is, printen zonder fillament is erg slecht voor de printer, verder gaf Rutger aan dat het een goed idee is wanneer je 2 rollen met elkaar zou kunnen verbinden, wanneer de eerste dan op is kan de volgende worden gekoppeld aan die rol.

Hij ziet het worden toegepast in de medische industrie waar producten op maat moeten zijn.

Insights interview Erik Tempelman



To gain better insight in how the market responds to Industry 4.0, look at the parallels with sustainability.

The design direction for the project is to take out the human factor.

The fact that materials and printers are relatively cheap causes people to just tinker with it. It is very easy to print something on a Ultimaker if it's not good user just retry it. This is opposed to when someone uses an expensive printer. In this case the entire process will be thought out well before printing starts as any error made will come at a price, this came with the benefit that expensive printers do have a much better workflow to prevent any mistakes from happening. This way there will be less trial and error in this workflow. When looking back at the cheaper printers, automating the workflow will become messy, so the cost perspective is important to consider.

For industry 4.0 it is important to look at the history as well as it is difficult to define the starting point of the fourth industrial revolution. The first is the most obvious one, the introduction of steam and coal power. The second revolution is considered the mass production by most, this was however, done far before Ford started doing so, it would be better to say that Electricity and Chemistry were the foundation of the second revolution. The third was the introduction of the semi-conductor and computers. The fourth is connectivity lead by the introduction of the IPV6 protocol which also marked the start of the internet of things.

An important book to read and utilize for the project is "het technisch Labyrinth" written by Harrie Linssen. (Deze heb ik alleen kunnen vinden van M. Pieterson, lijkt wel het boek te zijn wat er is beschreven). This book describes the first 3 revolutions and their implications.

Each new technology can be considered at 3 levels. The first being objects (artefacts), the second are institutes that are involved. Here you can think about financiers, insurance companies and companies that hand out norms. The third level is justification, the various (political) targets in level three will often conflict, for industry 4.0 there are a range of different versions each containing their own promises. The first place where Industry 4.0 was described was the Hannover Messe, some of the promises on industry 4.0 were making the industry more standfast, better products, faster production, human robot interaction. It is important to get an overview of the important factors.

When taking humans out of the loop it will become possible to increase the scale of production. Sustainable developments look at the WCED, in the 90s an important foundation for current sustainable developments was made. Have a look at what are relevant developments. When asking technologists what sustainable developments there are will be a wide range of answers. A lot of the articulations will conflict (like saying there will be more jobs available in industry 4.0 while also increasing automation). Carbon fiber for cars is a great example of this.

APPENDIX E

It is lighter and more durable than most of the traditional materials, making cars more energy efficient, however it is nearly impossible to recycle meaning that the total life cycle of a car made with carbon fibers is less sustainable. Industry 4.0 has been developed over the past years, the next step will be the promises that are going to conflict, those conflicts are certain to arise so it will be important to realize, what exactly are we doing? This way the developments can be justified. Smart industry, there is a lot of meaning inflation to that term. It is a lot the same but under a different name. A good practical example is the fact that EDI (Electronic Data Interchange) was introduced at DAF in 1999, this meant an EDI with suppliers, a shared partner system at the supply selection and the orders of parts. Back then a lot was already automated with lean manufacturing. Lean manufacturing is something that stands parallel to Industry 4.0. Lean engineering is now surfacing, especially supported by modern CAD systems. In my experience there are to much people that talk about industry who do not have sufficient knowledge on what is currently already possible with CAD and Internet.

Have a look at the book "the machine that changed the world". It reports on the biggest industrial project and contains a lot of data including promises made about smart industries. The differences between smart industry and lean are a lot smaller than it seems. Also initiate in a conversation with Bas van Deursen as he can tell a lot about the way Ultimaker sees the step towards the industry.

Insights interview Process & materials team FDM printing

Hoe sla je dan die data op en wat voor formaat en hoe zorg je dat machines met elkaar kunnen praten, moeten we standaard interfaces definieren? En ik heb een presentatie, die mag je van mij wel lezen maar moet je niet herdistribueren. Wij hebben met een groepje mensen door die roadmap heen gekeken, want astm maakt een roadmap waar ze de aandacht aan willen besteden met betrekking tot standaarden en daarbij met een aantal mensen samenvatting van de interessante punten gemaakt, daar zul je ook best wel iets tegen komen dat gaat over dat soort dingen, hoe zijn de digitale standaarden op de interface. Verhaal van de concepten...

Ik kan me voorstellen, ik ben heel lang geleden bij Porsche in de fabriek geweest waar ze ook onder andere motorsteunen voor porsche, gieterij giessen ofzoiets. Maar er was een heel grote metaalgieterij en die deden dus gieten in zandvormen en die maakte dus ook motorsteunen voor porsche. In dat proces werden dus al die motorsteunen gescant en dan werd dat opgeslagen en later ging zo'n motorsteun misschien kapot, dan konden ze die scan terug halen van toen het gefabriceerd was om te kijken, zat er misschien een luchtbelletje in of wat dan ook en moeten we misschien op die manier onze kwaliteitscontrole bijstellen? Dat vind ik ook I4.0, dus ik snap nog niet helemaal precies wat voor jou de aanleiding is om een fysieke printer te gaan ontwerpen als concept. Je zou ook kunnen zeggen, bijvoorbeeld ik ga printen in een fabrieksetting met een FDM printer, wat is nou de belangrijkste data die je zou moeten opslaan om tot een goed kwaliteitsbeeld te komen van een printen, dan kan je misschien een scenario schetsen waarin je uiteindelijk een geprint onderdeel in een bepaalde setting kan gebruiken, dat je digitaal gekwalificeerd hebt omdat je bijvoorbeeld weet nou, tijdens het printen is de flow nooit beneden de zoveel procent geweest, of de temperatuur en het bouwvolume. Dat soort dingen zou ik me ook voor kunnen stellen, dat lijkt mij ook heel erg industry 4.0 maar ik vraag me als buitenstaander, terwijl ik niks van je project af weet. Als ik je opdracht hoor van, nou, zorg dat je dus eigenlijk zoals jij het zegt slimmigheid toevoegd in een productielijn, wat is dan de aanleiding om een soort van station van een printer neer te zetten.

Dus je wilt kijken of je een concept kan neerzetten waarbij je zo min mogelijk menselijke operator time nodig hebt om te printen en wat zou dan daarvoor nodig zijn. En wat zegmaar is een stuk dat je aan de menselijke operator time weg haalt, ja ik denk dat ik toch nog niet helemaal overtuigd ben want dit is volgens mij gewoon automatiseren, bij industry 4.0 zou ik zeggen hoe maak je nou optimaal gebruik van het feit dat je tijdens het hele productieproces allerlei digitale informatiestromen hebt. Want eigenlijk als je aan het printen bent, die printer heeft een sensor in de kop en die meet bijvoorbeeld de temperatuur terug van de nozzle en die data is er dus in principe gewoon. Alleen daar wordt behoorlijk op geregeled dus daar sturen we het verhittingselementje aan, Maar ik zou me ook kunnen voorstellen dat je dat gewoon ergens opslaat en dat je dan weet, bij deze print was de temperatuur altijd

APPENDIX E

binnen die en range. Misschien is dat een beetje mosterd na de maaltijd.

Dat is juist erg nuttig en ga ik mee nemen in het uiteindelijke proces.

Wat ik ook een erg interessante stap vind waar nu nog een hoop mensen in zitten, als je een tekening van een kubus in solidworks maakt of welk cad programma dan ook, dan maak ik een doorsnede, dan is dat gewoon een massieve kubus, prima, dus ik heb allemaal informatie, misschien heb ik ook informatie over welk materiaal die kubus is en hoe zwaar het is. Dat betekent dat die kubus zo en zo zwaar is, misschien heb ik ook wel informatie over toleranties van die kubus, dat kan je gewoon doen in zo'n 3d model, in step format zit het gewoon in het format verwerkt. Dan doen wij het in STL, dat is al zo'n 30 jaar oud, misschien nog wel ouder uit de jaren 70. Dan gaan we dat hele mooie cad model met alle informatie, we gooien alle informatie weg en maken er een stl export van en dat is een soort benadering, dat ligt nog aan de instellingen of het een goede of slechte benadering is. Dat gaan we dan in de slicer stoppen en dan moet ik ineens allemaal dingen gaan instellen, dan moet ik instellen, standaard pakt die 20 procent infill, maak ik in mijn slicer een cross-section en dan is die ineens niet meer massief, dan is het een ding met een of ander patroontje er in en dan vervolgens ga ik dat exporteren naar Gcode, dan heb je ook weer een andere representatie dat is volgens mij uit de jaren 50 toen de CNC machines op kwamen en gooi ik weer alle andere data weg. Ik ben nu aan het praten over die digitale informatiestroom en aan het begin als mens stop je er informatie in en je bedoeling, welke vorm en tolerantie enzo. Een stuk van die informatie gooi je dan weer weg en dan ga je in een ander programma als mens weer informatie toevoegen, dan moet je weer instellen wat voor infill enzo dat stuur je naar die printer en daar ga je allemaal dingen doen. Je kan dus ook onderweg vergelijken wat ik nou aan digitale informatie heb, klopt dat dan nog wel met het begin of in ieder geval kun je het inzichtelijk maken, als er dan later een onderdeel uit komt wat niet is wat je bedoelt had dan kun je ook terug zoeken welke stap heb ik nou welke bewerking en wat heb ik gedaan in welke stap. Want het is ook nog zo, in cura kun je gaan schalen, misschien heb je straks wel een engineer die denk nou dat ga ik met die en die maten maken, dan gaat een operator het ergens printen, en het is een slimme operator, iemand in de fabriek die een tooltje maakt. Die heeft dat apparaat en denkt dat past niet. Want die man die gaat terug naar degene die het geprint heeft, die zegt ik doe het in cura een half procentje kleiner en daarna wordt het steeds geprint, dan gaan ze het in een andere fabriek ook gebruiken, maar dan hebben ze ook weer dat het ineens te groot is. Die engineer die het in het begin getekent heeft heeft nooit feedback gehad dat het ding misschien een beetje te groot is. Ligt het dan aan het ontwerp? Of misschien is het ergens in het proces dat de tolerantie van het ontwerp niet klopt met de tolerantie van het proces. Dat zijn ook allemaal dingen waar de mens een rol speelt en dan zijn we nog niet eens bij de machine. Ik probeer gewoon even kritische vragen te stellen en uit te zoomen, want je bent heel concreet met een tekening van een machine.

Timeline

Ik ben wel benieuwd, ik heb natuurlijk niet in detail gekeken maar eruit als een interessant plaatje van wat gebeurt er op welk moment in het proces. Hoe is de link tussen wat je net liet zien, de plaatjes van de machines en dit. Wat veranderen die hier aan of hoe is de link hier tussen, zit dat dan vooral in het laatste stuk. Waar zit de slicing dan bijvoorbeeld? Het is misschien wel interessant om dat toe te voegen of ergens een overzichtje te maken van wat is nou (dat stuur ik je ook door een slide uit een presentatie waar stapjes in staan).

Wat ik ook interessant vind, dat is ook een stokpaardje van zjenja maar ook wel van Jo, hij komt natuurlijk uit die 2d print wereld en heeft daar ook die overgang meegemaakt van analoog naar digitaal. Eerst had je meer het analoog drukken en printen. Als je gewoon een drukpers hebt, dat is analoog en dan moet je ook in tooling investeren en op een gegeven moment krijg je dat je digitaal kan werken en dan kan je gewoon een machine maken die heel productief is, maar die het niet erg vind om heel veel verschillende plaatjes/documenten te maken, dan is het voordeel dus dat je niet in tooling hoeft te investeren en omdat het digitaal is, je vrij gemakkelijk in het digitale een aanpassing of bewerking kan doen en dan, als je de machine digitaal aan kan sturen en je wilt het ergens anders op de wereld doen, dan hoef je geen mallen over de wereled te sturen of ergens anders nieuwe mallen te maken, maar dan kun je gewoon digitale bestanden doorsturen. Dus ook als je een trucje in de ene fabriek kan. Dat zien je nu bijvoorbeeld ook met die jigs en fixtures, stel dat volkswagen fabriek op de ene plek allemaal jigs en fixtures heeft gemaakt om een bepaald model auto te maken, als je dat ergens anders wilt doen dan hoef je niet die onderdelen rond te gaan sturen ofzo. Je kan gewoon een file opsturen en dan kunnen ze datzelfde deeltje daar ook maken. Alleen is het wel zo dat die fabrieken met elkaar concureren dus het ligt er een beetje hoe dat bedrijf is ingericht. Het is alleen het stukje over printen, dus niet hoe is het verbonden met de ERP of met het PDM systeem ofzo, maar ik heb alleen een plaatje van hoe is de workflow van cad model naar geprint onderdeel. (laat andere timeline ziet). Ja precies, wat ik dus interessant vind is dat je niet op 1 plek maar op verschillende plekken invloed hebt op wat nou de eigenschappen zijn van het gerpintte onderdeel, dus als je bijvoorbeeld onderextrusie krijgt, dat is Jim Floor die hier werkt, die heeft ook afstudeerprojecten bij industrieel ontwerpen gedaan en is heel erg bezig geweest met het meten van mechanische eigenschappen van ge3d-printte trekstaafjes. Wat je dan ziet is dat wanneer je 10 procent onderextrusie hebt dan heb je al 30 procent minder sterkte, dat is een beetje grofweg gegeneraliseerd, het hang natuurlijk ook af van de richting. Dat zou je kunnen zeggen, de hoeveelheid materiaal die je hebt neergelegd heeft heel veel invloed op de uiteindelijke sterkte, dat kun je dus uiteindelijk

APPENDIX E

beinvloeden in je slicing stap, maar het kan ook nog zo zijn dat er tijdens het printen iets gebeurd, dus de nozzle is per ongeluk te koud want er zit een fout in de sensor, daardoor heb je meer weerstand in de kop en dus onderextrusie. Het kan ook nog zo zijn dat er iets gebeurt met de embedded firmware en dat iets doet met versnellingen. Blijkbaar kan onze printer niet zo heel goed om gaan met hele snelle verschillen in flow, want het is niet zo heel erg dynamisch door de bowden tube. Dus als je bij de feeder een snelheidsverschil maakt dan duurt het een tijdje voordat dat snelheidsverschil bij de kop is aangekomen (zeker met flexibele materialen), ja dus het hangt ook nog af van het materiaal, dus als je met een ander materiaal print kan dat ook effect hebben. Dus binnen dat hele proces van 3d printen heb je op verschillende punten invloeden. Bij het cad model heb je invloeden op de eigenschappen, want je hebt bepaalde geometrie, dan bij de export heb je nog invloed op de eigenschappen want als je niet goed exporteerd en met te weinig driehoekjes dan krijg je msischien wel een andere vorm, dan heb je nog in de slicing software invloed en kan je aan de knoppen draaien om dingen aan te passen en dan ook in de printer kun je nog dingen aanpassen, in de 2+ kon je bijvoorbeeld de flow instellen, dan nam die een factor, dan ging die kop sneller bewegen en ging die sneller extruderen maar de nozzle werd niet heter, terwijl als je sneller gaat extruderen en je zet de nozzle niet heter krijg je meer weerstand, dan gaat die slippen en krijg je meer onderextrusie, dus wordt je onderdeel slapper. Je kan op de printer ook nog de nozzle temperatuur aanpassen, allemaal dingen waar mensen aan kunnen zitten. Een hele boel van die informatie zou je beschikbaar kunnen maken in het digitale domein.

Op een gegeven moment hadden we op de Ultimaker 3, dan kon je wanneer je inlogde op de printer je ook alle meetwaardes kon loggen van allerlei sensoren in de printer. Ik zou dus bijvoorbeeld kunnen voorstellen dat het in zo'n Industry 4.0 situatie het heel interessant is om gewoon procesdata terug te hebben en dat je daaraan kan koppelen. Misschien kan je het ook leren dat als je op een gegeven moment inspectie doet en dat je denkt van nou er zit een ding in de printer wat materiaal flow kan meten, of je weet als je de nozzle temperatuur en de druk op de nozzle weet dan is dat ook een goede indicator van een materiaal flow en dat je zegt, ik ga er naast meten hoe sterk of precies een onderdeel is en dat kan terug koppelen. Dus alle onderdelen die in spec waren die hadden deze sprijding op de nozzle temperatuur, daar zou je best wel machine learning op toe kunnen passen. Dan kan zo'n proces zelf leren van wat voor tolerantie moet ik tijdens het printen hebben om aan bepaalde kwaliteitseisen te voldoen. Dat kan ook zijn dat je zegt als we echt voor industry 4.0 eem machine gaan ontwerpen, dan is het heel belangrijk dat we key proces parameters kunnen meten, ik heb met mensen bij Ultimaker gepraat en dan denk ik dat dit hele belangrijke parameters zijn, dat zou je in een concept mee kunnen nemen misschien. En ik denk dat het ook interessant is, van hoe kun je nou toch het wat minder warrig maken, het proces van het slicen wat je dus ziet als je kijkt naar hoe autodesk het doet bij Fusion 360, dan zitten daar al behoorlijke stukken als je kijkt naar traditionele CNC machining, bijvoorbeel frezen, dan zit daar best al een stuk CAM geintegreerd in het pakket, zo wordt dat steeds meer met elkaar geintegreerd met elkaar. Zodat wat je in CAD ziet ook meer klopt met wat er uit een machine komt maar ook dat je niet op 2 verschillende plekken je bedoeling er in moet stoppen, van wat bedoel ik nou als ontwerpen. Ik voorzie wel dat je in de toekomst steeds meer cura achtige dingen en simulatie dingen in CAD integreerd. Voor spuitgieten zie je dat ook, want er zit een tool om je lossingshoeken te integreren in solidworks.

APPENDIX E

Insights interview R&D department

Climate control in de bakken hangt heel erg van het materiaal af, PVA is notoir vochtabsorberend. Daar is het specifiek voor ge-engineerd. Zijn er mee bezig dat proces aan te passen, dat PVA in filamentvorm wordt gerekt en een kristallijne buitenkant krijgt waardoor het geen vocht op neemt, maar het moet natuurlijk wel super snel oplossen in water, dat is een conflict dus wat dat betreft is PVA het grootste probleem. En alle high temperature polymers, die nog niet op de ultimakers draait maar wat wel handig is voor de industrie zoals PPSU, PEEK, Vespel. Die zijn ook allemaal erg gevoellig voor vocht omdat een paar procent vocht je eindproduct verpest. Nylon geldt hetzelfde voor, het moet ook binnen een bepaald gebied blijven, nylon heeft als nadeel, als het kurkdroog is dan kan je er niet mee printen want dan is het zo bros als glas, dus je hebt een werkgebied maar dat is erg afhankelijk van het polymeer. Dus het is vooral de luchtvochtigheid. Temperatuur van de opslag maakt niet zo veel uit. De temperatuur versnelt of vertraagt de uitdroging. Johan bewaart al zijn high performance polymers, PEEK, PPSU, ULTEM, PEI, die staan altijd in de oven, structureel op 90 graden, daar kan het tegen en is het voor gemaakt. Daardoor is het droog wanneer het de printer in gaat. PVA bijvoorbeeld, dat wordt altijd op kamertemperatuur bewaard, zolang het maar afgesloten is.

Wat betreft bepaalde chemicalien in de lucht die invloed hebben, het filament moet schoon blijven. Maar dingen uit de lucht, dus wat conditionering betreft. Als een rol in een bepaalde luchtvochtigheid wordt bewaard waar continu allemaal zuren langs komen of iets dergelijks, dat is iets waar Ultimaker totaal niet mee bezig is. Er wordt aangenomen dat je in een omgeving bent waar mensen mogen rondlopen, wat dat betreft is het materiaal veilig. Daar wordt het spectrum ook op afgesteld, als de lucht voor mensen veilig is, dan zit het met de materialen ook goed.

Om die bakken goed te houden kan je er het best droge lucht naar binnen blazen, dat is wat ze bij fabrieken vaak doen, de pick and place machines waar Johan mee werkt daar wordt gewoon of stikstof of droge lucht naar binnen geblazen, dat zorgt voor een constante overdruk, daarmee blaas je al het stof naar buiten en de machine blijft droog. Dat is een beetje de standaard oplossing.

De printomgeving, op het moment dat de materiaal uit de extruder komt, hoe belangrijk is de omgeving in die printruimte, naast de warmte natuurlijk? Dat ligt er aan, bij de PEEK printer bijvoorbeeld zit het filament veilig maar wat Stratasys bijvoorbeeld doet. Filament zit in een conditioned doos, het filament komt er uit en gaat door een onwijs lange buis naar de nozzle toe. Voordat die Stratasys gaat printen purged die de hele buisinhoud, want ze zeggen, dit stukje hebben we geen controle over. Bij de Fortus printers, die zijn nog weer duurder, daar zit gedroogde perslucht in en die loopt door het hele systeem tot de nozzle. Daar wordt het gehele filament gedroogd zodat je niet hoeft te purgen. Dus het is vooral het stuk dat hier stilstaat, waarvan je de status niet precies weet moet je het weggooien, of retracten of in ieder geval weghalen uit die omgeving. Een ander nadeel is ook. Printen duurt heel lang, als die tube heel lang is, dan kan de tijd dat het daar in zit kan enorm oplopen. Dan heb je het over uren al snel. Bij nylon is dat niet zo belangrijk, bij PVA kan dat veel uitmaken. Als je bijvoorbeel in India een printer neerzet op de verkeerde plek dan heb je er last van. Na het extruden is het een object. Bij Nylon heb je bijvoorbeeld als je dat print en je wilt het transparant hebben dan moet je dat op een hogere temperatuur doen, dan stoot je al het vocht er uit, dan moet je je object eigenlijk een halve dag op je printplaat laten zitten. Nylon werkt het beste met een klein beetje H-bruggen. Dus dan moet er 2 tot 5% water in zitten voor zijn stevigheid en ductility. Dus op het moment dat het net geprint is is het mooi transparant en witte nylon prints zit een beetje water is. Dus als het heel transparant is is het bros en dan moet je wachten met het eraf halen. Dat heb je met nylon, PSU en voor de rest heeft UM geen materialen die dat ook hebben. PLA ja dat heeft zo'n breed gebied voor alles dat het niet uitmaakt wat je daar doet. ABS neemt geen vocht op PC ook niet.

Wanneer je de build plate wilt gaan verplaatsen van A naar B dan moet je hem warm houden, plus dat je te maken hebt met thermische krimp wat er ook voor kan gaan zorgen dat het los gaat. Je print het in een kamer die warmer is, zeker waar wij nu naar toe gaan, uiteindelijk gaan alle printers naar een temperatuur van 80 graden (C) omdat je dan de beste objecten print. Dat geld voor eigenlijk alle materialen behalve PLA. ABS rond de 60-70, Nylon vanaf 80, PC vanaf 80 alle glasgevulde en carbon filled materialen hebben er minder last van, want die krimpen niet zo erg want die worden door de vezels op hun plek gehouden. Polycarbonaat heeft best een grote thermische krimp, als je dan de built plate warm houdt kan het alsnog zijn dat die los komt. Dat hangt dus heel erg af van hoe je je proces inregelt. Het kan zijn dat als je het in de oven af laat koelen dat het wel goed gaat. Of dat als je een raft print het wel goed gaat. Maar je hebt met thermische krimp te maken.

Kwa feeders, op het moment dat je junctions hebt, dan zul je ongetwijfeld her en der feeders nodig hebben. Wat je krijgt, je hebt een feeder in je printkop, want je wilt zo dicht mogelijk bij de nozzle een feeder hebben, het liefst er in maar goed dat is lastig. En je hebt ergens een pre-feeder die het materiaal aanvoert. Alle oudere FDM printers, die hadden een motortje bij de ingang zitten die een beetje het filament naar boven duwt die zorgt dat er niet te veel spanning op staat en de ander zorgt dan voor de procescontrole en dan zit er ergens een bufferloop, of dat wordt digitaal geregeld. Zoals het nu is zijn dat altijd cardridges die je er in doet. Bij Philips hadden ze zoiets we gaan met pellets printen, dat was een veel groter project, die hadden een printer van 1 bij 1 meter waar er 8 van werden neergezet met een silo pellets ernaast.

Voor het verwarmen van de printers,

APPENDIX E

theoretisch gezegd, er zullen warmte-elementen in moeten zitten. Op het moment dat de ruimte wordt verwarmd dan kan dat niet meer met het bed. Er is 1 materiaal, daarbij moet de ruimte zelfs warmer zijn dan het bed en moet het bed dus gekoeld worden. Dat is een situatie die voor kan komen bij een bepaald materiaal met bepaalde eigenschappen, waarom mag niet worden gezegd. De temperaturen van die 2 moeten dus los van elkaar worden gezien. Je hebt dan ook de laat waar plastic op plastic wordt geplaatst en het volume waar dat object staat, dat wordt ook bedoelt met die thermische krimp. Het plastic komt uit de nozzle met 200+ graden koelt af naar een temperatuur, daarbij heb je krimp en vervolgens naar kamertemperatuur waarbij weer krimp volgt, dit moet allemaal gecontroleerd gaan. Het concept kan dus wel werken, het beperkt echter het aantal materialen dat je kunt gebruiken, of in ieder geval de grootte van je object. Bij hele kleine objecten heb je minder problemen dan wanneer je het over grote objecten hebt. Massieve veel groter probleem dan hol. Dus dat moet wel worden meegenomen.

Insights interview software / algorithm engineer

Bij het nieuwe interne hardware project binnen Ultimaker word getest met kinematic coupling. Bij deze printers hangt er naast de nozzle een afstandsmeter omlaag en die moet er makkelijk op en af gehaald kunnen worden en daarom kinematische koppeling want dat is erg nauwkeurig.

Bed levelling wordt in de eerste centimeter afgebouwd, daarna is de bed-levelling dus niet meer belangrijk maar hoe goed je de z op dezelfde hoogte krijgt, dat is 1 van de dingen in de UM, onderin zit een limit switch, wanneer die wordt aangetikt is de maximale buildhoogte bereikt, daarna beweegt het printbed omhoog, deze switch is niet erg nauwkeurig, dus als er tijdens het printen opnieuw moet worden gehomed dan kan die onnauwkeurigheid er voor zorgen dat de z niet precies op dezelfde hoogte staat als de vorige keer. Dat kan de enige fout zijn, de bed levelling zou voor geen probleem moeten zorgen. Bij het eruit en erin halen ben je precies het tegenover gestelde aan het doen als wat er bij UM intern gebeurt, waar wordt geprobeerd dat de omgeving kwa temperatuur zo constant mogelijk is en waarschijnlijk op het eind een langdurig afkoelproces moet zijn zodat het rustig en gelijdelijk afkoelt en krimpt. Als je het dus meteen uit de printer zou halen dan kan dat effect hebben. Dan heb je een afgekoeld part en die wil graag los van zijn bed laten. Op formnext waren er printers van 30 meter lang waar het van kamer naar kamer ging. Zodra je een part gaat afkoelen naar kamertemperatuur en daarmee moet vervoeren denk ik dat je problemen gaat krijgen. Wanneer een plaat vervangen gaat worden moet die warmteplaat mee gaan.

Het lossen gaat vrij snel, dit verschilt erg per materiaal, PLA kan er relatief goed tegen, ABS gaat gelijk krullen. Dat wil niet zeggen dat het conceptueel niet kan, er zitten gewoon wat problemen maar daar valt wel omheen te werken en op te lossen. Het is belangrijk dat elke stap in je proces gecontroleerd is. Zodra er dan bijvoorbeeld een windvlaag langs komt dan koelt je part af en gaat het mis, zo hebben we nu bij de s5 een deurtje erin geplaatst, dat is al een hele verbetering.

Bed-leveling is dus zoals we het nu doen in de eerste centimeter bouwen we het af. Je kan het ook op andere manieren doen, die de scheefstand van je bed compenseert door het part enigzins scheef te printen, dat hang heel erg af van hoe je het doet.

Cura weet niks over de scheefstand en gaat er vanuit dat het bed vlak is, het enige wat er gebeurt is dat er wat hoger of lager wordt geprint, er wordt niks aangepast aan de lijnbreedte. Bij de onderste lagen heb je dus pieken en dalen en daar wordt een lijn doorheen getrokken, dat is het 0 punt, dat wil dus zeggen dat er in die dalen te weinig materiaal ligt en in de pieken teveel. Doordat er een cm over wordt gedaan valt het mee hoeveel dat is. Je kan het met een raft ook anders doen door eerst een kort laagje support ertussen te doen, deze zit los-vast aan het part, je print een aantal wijde grids aan het part. Door dit met bijvoorbeeld PVA te doen (water oplosbaar) krijg je dat het gehele part een gelijke uitstraling heeft, ipv 1 kant (die aan de glasplaat zit) die helemaal glad is.

APPENDIX E

Er worden steeds meer andere soorten printbedden gebruikt, bijvoorbeel met een texture erop, dit zorgt voor een betere adhesion, alleen wil Ultimaker het daarom niet, adhesion kan je op andere manieren oplossen. Wat UM wil is een plaat die met meerdere materialen werkt en goedkoop is. Met sommige materialen kan het printje te goed op het glasplaatje vast zit waardoor je stukjes uit het glas trekt. Het glas gaat nu ook nog langer mee dan alle andere oplossingen. Wat ook niet anders kan, zo'n texture suggereert dat er allemaal vervuiling in zit. Eigenlijk wilde UM ook een aluminium plaat hebben, maar de leverancier kan ze niet voor een goede prijs helemaal plat krijgen en ook met de coating zijn er problemen. Deze wordt dus helaas ook niet geleverd met de s5, daar kregen klanten een voucher voor. Er wordt nog gekeken naar andere leveranciers, de leverancier kon het uiteindelijk niet meer helemaal vlak en met de goede coating leveren voor de initiele prijs waardoor dit niet meer is doorgevoerd.

Voor een goede hechting is het belangrijk dat de plaat vetvrij is, een lijmstick kan werken of een oplossing van ABS. Het belangrijkste hierbij is dus dat de plaat goed vetvrij is. Bij het vetvrij maken wordt gedacht dat de goede adhesion komt doordat de part vacuum komt te zitten op de plaat, wanneer je dingen gaat toevoegen ga je dit tegen, maar als dit goed genoeg plakt is dat weer het leidende effect voor de adhesion en soms heb je daar een beter resultaat mee. Het hangt af van het materiaal. PETG is bij UM CPE+.

Insights interview Software Developper

- .3MF
  - Digital thread file
  - Still geometry based
- Contains 3d model data
  - Tolerances
    - No slicer that uses those
  - Serial numbers
    - Ability to make it hybrid
- Example the airplane industry
  - Each part has its own serial number
- Slicing is not the problem, that is 4% of the work a slicer does
  - Toolpath is the difficult part

Signing the parts is important, especially with parts that need to be re-validated. What we are looking into is having the integration better. This works in 3mf which is integrated in the slicer as well. That can be connected to a printer, making sure that printer is only capable of printing parts that have the correct signatures and are validated. In case a junior engineer makes a change and sends that then you don't want that to accidentally to be used in production. Ultimaker does not support this yet, but will add it in the near future. We also expect more sorts of simulation in the future on gcode, that will add more checks. We now have the physical check but then also include the check whether it came from a trusted source and check if a simulation has run on the part and if the results are within a certain threshold. These kinds of simulations will be Finite element models, so it is modeled and then a simulation is done which takes a lot of time, but I'm talking about a simulation for a part that will be printed thousands of times, so the simulation does not take up too much of the entire process, where it makes sense to even have a 30-day long simulation, to validate that it will work in all the situations that it is printed, this way things like warping can be simulated in advance. It can then be verified that a print will only be done if a file has had those simulations.

To put a number on a print you can also encode not only a unique identifier but also encode some information regarding a spool number for traceability to connect that information, dependent on the application.

Sensors in the Ultimaker. The thing is about as open looped as it can get. One of the only things Ultimaker has is temperature control and that is because they absolutely need that and the S5 is slightly better in that regard because it has a flow sensor, but if a printer misses a step it has no clue that it happened. That is mainly done because it is cheap and simple. For this it is important to keep in mind that there is a migration from the consumer and hobbyist market to the companies' market, where price is everything. Ultimaker has been working in a way where there is a short deadline so the machine has been kept mainly the same and only changing the things that absolutely have to been changed. That's also why the um 3 also has this weird screen, there was no time to adjust and test any changes since the product had to be pushed to the market. A lot of those things, like the small amount of sensors has to do with that, long story short, the first printers of Ultimaker were not intended for the industry. A lot of the things in the field of accuracy and reliability can be met with the software in the means of profiles.

The reliability of the prints can be done with an accuracy of 50 micron with a high repeatability due to these software profiles.

APPENDIX F

First layer sensors

Manual Leveling

Manual leveling is common in most printers, to adjust the height of the printbed, Ultimakers have 3 screws that can be adjusted to raise or lower the printbed and adjust skew. Some printers have 4, this can lead to the printbed being bend by the fourth screw along the diagonal plane of the bed.

Software Leveling

Some printers that do not have a way to adjust the bed manually (like Prusa printers), have a software solution. The control board of those printers stores the data of the bed and adjusts the Gcode in such a way that the first layer is printed parallel to the printbed.

Inductive Probe

Used by various printers (Prusa i3 Mk2, Pulse, Printrbot Simple Metal and more). The location of a conductive metal in the build platform is sensed precisely by this probe. Z-offset values are required to at the proper level as the probe does trigger precisely, its 0 can be above or below the bed. This offset value has t be calibrated once and can then be re-used.

Lulzbot Style Probe

A wire is connected between the control board and the hot end of the printer. 4 Other wires are connected to washers in the corners of the printbed. At the start of each print the nozzle is wiped and then probes each of the corners. A disadvantage is that the nozzle has to be absolutely clean, which it often is not causing the nozzle to slam in the washers as the circuit is not closed.

Capacitive Probe

Used by Ultimaker, the bed is first leveled manually to get the bed as level as possible. The printer then measures the points that were leveled manually to increase the accuracy and compensate for any deficit. The first layers are then printed skewed until the top layer is flat (this happens in the first cm (Marx, S. 2019)). A small chip between the print head and the aluminum of the printbed measures the capacitance (Ultimaker. 2016). The chip measures when the capacitance changes as the print bed moves towards the head. It is a reliable way of leveling the bed. (Matterhackers. 2018)

Microswitch

A switch sends a signal when it is pressed.

IR Sensor

An IR sensor is attached to the extruder sending a signal when the bed and nozzle are close enough to each other. 9 points in a 3 by 3 grid are probed which results in a mesh of the bed. The sensors are sensitive to the reflectiveness of the surface meaning that glass or PEI will need an opaque backing to work with these sensors. The sensors do work accurately, but the repeatability is heavily dependent on the quality of the sensor.

Touch Probe

Touch-sensors make use of the “Hall Effect” where a sensor triggers in the presence of a magnetic field. This type of probe extends a small metal rod that touches the bed and registers the Z0 point. This sensor works with glass, Buildtak, aluminum PCB, blue tape, PEI or any other material; as long as it can touch something, the probe is able to measure it.

Accelerometer

Some printers have an accelerometer integrated in the extruder. To measure the bed, the extruder first moves over the center of the bed and taps it with the nozzle using the accelerometer to measure where it stopped. It will do this a couple times to get a good average of where 0 is, and then begin probing at the base of each tower.

Force Sensitive Resistors

This sensor uses resistors under the bed that increase their resistance under force. The nozzle and bed need to be clean for this to work. These resistors are extremely sensitive with some having a 0.02mm repeatability.

APPENDIX G

G. Calculations for hourly print costs

Based on 30 cc/hr output extrusion rate and $25/kg generic retail material cost; cost per hour in material is $0.75/hr. with an industry standard failure rate of 25.3% and assuming the material used in those failed prints is not recoverable, the cost of material production raises to $0.94/hr. With closed source printers such as the Fortus production line made by Stratasys, the material cost will on average be much higher at around $250/kg. with an effective material consumption cost of $7.5 per hour.

Basing the above on the 30cc/hr output rate, the cost of just labor and raw material for each kg of parts produced using generic materials comes to $39.67 per kg with our automation platform and $68 per kg without our platform. The cost of production without our platform and using proprietary materials is approximately $286.68 per kg. However, to understand the full cost of production we must also include electricity and space as well. To do that we will settle on average values between the different printer models and apply them to each category.

Using a $0.15/kWh electricity rate and 600W average continuous power draw from the printer and support equipment, the cost of energy for each printing hour is $0.09/hr. With applicable failure rates accounted for (25.3%), that effective rate reaches $0.113/hr. Based on the 30cc/hr output rate, that comes to an additional $3.76/kg when not using our platform and $3.25/kg when using our platform. Our SCADA application has been shown to be able to save approximately 30% on factory level energy usage by exploiting account specific discounts or avoiding peak charging. Therefore, the average energy usage cost with and without our platform is closer to $2.76/kg. and $4.89/kg. respectively.

To account for space, we will base our calculations on each printer effectively requiring 80 sqft and the cost of space being $0.50/sqft/mo. Printers on the SD3D platform are shown to have an improved uptime by approximately 38% due to the lower failure frequency and ability to auto eject parts while unattended. That corresponds to the following costs per kg produced based on the 30cc/hr extrusion rate: $1.16 with our platform and $1.85 without our platform

The true combined variable cost of production for space, energy, material and labor costs are therefore $43.59/kg with our platform and $74.83/kg without our platform when using generic materials and open source 3D printing systems. When using proprietary materials such as with the Fortus line of printers by Stratasys without our automation platform, costs can exceed $293.42/kg in production. By using our automation platform, these materials may be substituted with generic alternatives without risking any loss in print quality or reliability.

APPENDIX H

Digitization, digitalization and digital transformation

Digitization: Transitioning from analog to digital

This is where it all began. Years ago, and sometimes still today, business processes were analog. If you had a device in need of repair, you would call the manufacturer who would fill out a work order form explaining your issue. A service technician would be assigned the task of making a field visit to assess, and hopefully repair the issue. All customer files, product manuals, repair handbooks were hard copies. This meant that the service technician would arrive with a stack of paper that might include anything from the customer's name and address to the product's history and a listing of replacement parts to a date book listing the day's appointments. Digitization is the process of making all of this information available and accessible in a digital format.

Digitalization: Making digitized information work for you

Once analog data has been digitized, there is enormous potential for applications that facilitate standard work practices. Field service providers can implement field service management (FSM) software like Coresystems to make smart use of digitized information. For example, centralized data about customers including contact information and product history help service technicians stay informed about their customers' previous issues and what types of problems they might encounter. This means they come prepared with an arsenal of current and background knowledge to assist in a smooth field service operation. In addition, information collected from different service technicians about the same or similar products can be compiled to create checklists for resolving recurring issues. This kind of knowledge sharing can also extend to product manuals, and video tutorials that are available on any mobile device. All these types of tools ensure that technicians in the field have access to as much information as possible to guarantee a first-time-fix.

Digital transformation

Manufacturing is undergoing a digital transformation driven by smart technology and connected devices. Amazon, for example, is increasingly removing "friction" from its end-to-end buying process by reducing the number of steps customers need to take in order to complete a transaction. They are now even exploring 30-minute delivery of certain items in certain areas. Amazons Dash service, incorporated into our appliances, automatically orders and delivers items like laundry detergent when sensors detect supply is running low. https://developer.amazon.com/dash-services The next step is for Dash service orders to be delivered by autonomous drones.

digitization-digitalization-transformation

Thanks to digitization and digitalization, data is easily accessible for use across various platforms, devices, interfaces. Digital transformation is the process of devising new business applications that integrate all this digitized data and digitalized applications. Consider the example of Netflix and Blockbuster. Once films were digitized, the path was paved for a completely new business model: movie streaming. These are the biggest game changers when it comes to digital transformation.

APPENDIX I

Companies implementing Industry 4.0

As found in KPMG report "Industry 4.0 beyond the hype"

The report included a number of benchmarking exercises which found that many organisations demonstrated only a low-to-medium level of maturity in key areas such as demand-driven supply chain, M2M communication, and digital twinning.

However, they showed somewhat better maturity in cloud, robotics, Big Data, cybersecurity and IoT technologies.

KPMG's Alec McCullie added: "Gaining experience with industry 4.0 technologies is certainly important. But the real value of industry 4.0 comes, not from the component technologies or capabilities, but rather through smarter processes that integrate automation, data, analytics, manufacturing and products in a way that delivers unique competitive advantages and unlocks new business and operating models. And this cannot be accomplished without achieving larger scale, greater integration across functions and a willingness to disrupt the status quo."

Rather than focusing on pure investment numbers and reported investment returns, this research focuses on identifying how the leaders of today's industry 4.0 revolution are driving value from their investments and preparing their organisations to take advantage of emerging opportunities in the future. The report also identifies areas where manufacturers could be taking a more integrated and strategic approach to industry 4.0 adoption. And, in each area, it offers practical advice for driving adoption and creating value.

"There are a number of key focus areas that are creating challenges for manufacturing executives across the value chain," continued McCullie, "particularly as they work to transform their organisations for the industry 4.0 environment. This includes issues such as developing a robust, goals-focused strategy, scaling up the programs, managing the impacts across functional areas, integrating with products and improving the value network."

"Success in industry 4.0 is not about how much you invest; the winners will not be those with the deepest pockets" continued McCullie, "to win in tomorrow's competitive and rapidly changing environment, manufacturers need to start being bolder in their vision, strategies and actions if they are to succeed."

APPENDIX J

DEPEST

Demographic

This factor addresses the composition of the population; greater understanding of this factor could be of crucial importance for an organization.

The population of the world has increased from 2.5 billion people in 1950 to 7.3 billion in 2015. It is expected to keep rising until between 2050 and 2100 in most variants predicted by the UN. In the average variant the global population will increase to 9.7 billion in 2050 and continue rising to 11.2 in 2100, if the fertility and mortality rate stay as is this number will be significantly higher, namely 10.2 billion in 2050 and 19.3 billion in 2100. (EEA. 2016)

The population of the 28 combined EU countries is projected to just slightly increase, from 505 million to 510 million by 2030 and then decrease to about 465 around 2100. This means a shift in age structure with 65 or older increasing from the current 19% to 30% in 2050 and even further to 43% in 2100 (in the average variant assumptions). (EEA. 2016)

Migration

Europe's population is influenced by a number of factors among which, migration, fertility levels, life expectancy and the respective strength of job markets. (Harris, B. 2017)2015 was the first year on record with more deaths than births across the 28 EU countries. (Harris, B. 2017)

The information is contained in an extensive annual yearbook compiled by Eurostat, the statistical office of the EU, and recently released for the year 2015. (EC Europe. 2017)

While migration can play an important role in the population dynamics within many of the EU member states, the report notes, it's unlikely to reverse the overall trend of population ageing. (Harris, B. 2017)

Economic

These are all factors that have to do with economic growth, inflation, purchasing power, etc.

In a research done by Sculpteo (with professionals from the 3D printing marker), it was found that in general there is an increasing number of people owning 3D printers. 66% of the participants own one, of which 44% own multiple printers. Looking at the reasoning behind this increase it was found that people wish to use 3D printing for more applications. Buying a 3D printer has increasingly become a long-term priority where 17% said they will purchase one, against 10% a year earlier. Multiple 3D printers are needed for companies to experiment with different 3D printing techniques in order to grasp the benefits that the technology brings to their product lines. (Zeijderveld, J. 2018)

It is estimated that the current economic trend is to continue but at a slower pace. With 2.3 percent the GDP of the EU in 2017 the growth was higher than expected, but an estimation of 2.1 in 2018 and 1.9 in 2019 have been made. The Netherlands, Germany and Austria are expected to perform better than their peers in 2018 but growth rates will moderate after that as well. (PricewaterhouseCoopers. 2018)

Consumer spending has been one of the most important factors of the Eurozone recovery and is expected to keep growing the coming years at a slower pace. More employment is seen as the main reason for this increase. Unemployment rates in the EU remain high with a predicted 7% for 2019. (PricewaterhouseCoopers. 2018)

It is expected that industrial manufacturing, automotive and consumer markets will contribute the most to GDP's in the following years. The highest growth rates have been estimated to be in the services sector, technology, median and entertainment and financial services. (PricewaterhouseCoopers. 2018)

The global marketplace: Although the industrial base in developed markets will continue to be eroded as jobs transfer to emerging markets, fears of the demise of Western manufacturing are unfounded. Developed manufacturing economies will still hold an advantage in high-value and capital-intensive activities; proximity to customers will also be critical for many. The industry landscape: The globalisation of manufacturing will continue apace, particularly in high-volume segments. The desire to move into higher value activities will encourage the emergence of original brand manufacturers (OBMs) in low-cost economies, manufacturers that design and produce under their own recognized brands. (Economist intelligence unit. 2016)

Changing relationships: The vast majority of manufacturing survey respondents expect to involve their customers and suppliers more closely in their product development processes. Responsibility for solving production problems will increasingly be devolved down to the factory floor. (IMF. 2017)

Corporate strategies: Generic and easily automated manufacturing processes will shift to low-cost locations, but rising demand for personalisation will lead many products to be customised locally. Efficiency throughout the supply chain will be a major source of competitive advantage. (Economist intelligence unit. 2016)

AM is changing how products are designed, developed, manufactured, and distributed. By

APPENDIX J

2021, the 3D printing market could be worth €9.6 billion, according to a report by the European Commission in 2017.

Political/judicial factors

These are all political measures at a decision-making, provincial and municipal level.

Attempts for a standardization of additive manufacturing are being made. Standards, specifications, and related conformance and training programs are integral to this process and are a key enabler for the large-scale introduction and growth of AM. (ANSI. 2017)

Although it is creating opportunities for companies, it is also raising challenges, especially concerning civil liability and intellectual property rights. French EFDD member Joëlle Bergeron has written an own-initiative report with legislative and regulatory recommendations in the field of 3D printing. (European Parliament. 2018)

Who should be liable when a 3D printed product is found to be defective or unsafe? Clear rules on who owns the right to a 3D printed product should help to fight counterfeiting, but also to protect the work of designers and printers. How do you see the industry's future? (European Parliament. 2018)

Ecological

This includes all factors in the area of the physical surroundings and the environment.

Warehousing: With current manufacturing technologies, consumer products are made in high volume for storage and then distribution. However, with 3-D printers, only products that are sold need to be manufactured. This means warehousing of extra inventory is decreased. Overproduction of product will also reduce cost. (SCW3D)

Global waste management has been neglected over the past decades. Far too much plastic has been improperly discarded into the natural environment. The litter affects biodiversity, enters the food chain and eventually has an impact on our health. Circular economy enforces eco-design, waste prevention, recycling and energy efficiency, which helps tackle the environmental pollution problem. Designing eco-friendly, easily recyclable and energy efficient products by using fewer resources would enable manufacturing durable goods that could be recycled into quality recyclates. As a consequence, the maximum of available resources would be restored and virtually no waste would be landfilled. Furthermore, this transition would result in a snowball effect by positively impacting our lives and health, and by saving natural resources, reducing Europe's dependency on foreign resources, and boosting creation of cleaner industries, jobs and technology developments. (EUROPEAN ENVIRONMENT AGENCY, 2018)

More efficient transportation = less pollution You could write hundreds of pages on the benefits that industrial 3D printing is bringing to industries such as aerospace, aviation, automotive and even energy production (in fact we do write hundreds of pages on these topics, in our Smartech Publishing industry reports). However, strictly in terms of immediate benefits to humanity, using 3D printing in industrial manufacturing can help in many ways. For example by reducing waste and producing on demand. However one of the biggest benefits is weight reduction through part geometry optimization. This can become cost-effective only through the use of AM and in the near future, it will reduce emissions from airplanes and cars by millions of tons. (Boissonneault, T. 2018) By the way, many current metal direct energy based 3D printing technologies (powder bed fusion and directed energy deposition) are very energy intensive. This, however, is an entirely relative issue if the energy used is produced from renewable sources placed near the production plant. In addition, upcoming technologies such as production level metal binder jetting may significantly reduce energy consumption. (Boissonneault, T. 2018)

Social/cultural,

These are characteristics in the area of culture and way of life.

In the research of Sculpteo a major shift in the level of expertise of the respondents was found. The research this year found that 15% see themselves as beginners, 41% intermediate and 44% as experts against last years 40% beginners, 40% intermediates and just 20% experts in additive manufacturing. (Sculpteo. 2018)

In a research done by Sculpteo (with professionals from the 3D printing market), it was found that in general there is an increasing number of people owning 3D printers. 66% of the participants own one, of which 44% own multiple printers. Looking at the reasoning behind this increase it was found that people wish to use 3D printing for more applications. Buying a 3D printer has increasingly become a long-term priority where 17% said they will purchase one, against 10% a year earlier. Multiple 3D printers are needed for companies to experiment with different 3D printing techniques in order to grasp the benefits that the technology brings to their product lines. (Zeijderveld, J. 2018) The respondents top priorities for choosing 3D printing were: 39% accelerating product development, 25% to offer customized products and limited series (which was 16% a year before) 19% Product flexibility and 19% had production flexibility as their top priority. The emphasize on customized products and limited series will increase with 26% expecting to get this as a top priority. An increase in experts in the field

APPENDIX J

of 3D printing and new ways of applying 3D printing having something special will be key. (Zeijderveld, J. 2018)

Cultural and archeological preservation

In the past years various terrorist organizations destroyed important works of art, shocking the world. This initiated artists, archeologists and non-governmental organizations to team up and remake, replace and protect the art for future damages. 3D scanning and printing technology has been used to rebuild and recreate priceless artifacts. (Boissonneault, T. 2018) 3D printing is also being used for education and making art and historic artifacts available for those who are visually or motion impaired. In fact, 3D printing service provider Materialise recently went so far as to 3D print a full-size mammoth. (Boissonneault, T. 2018)

Ultimaker ziet piek in Cura gebruik op werkdagen

Until recently Ultimaker saw the peek in Cura usage during the weekends. Nowadays it has been shifted to weekdays. This means, 3D printing is being done in a professional environment more often. This is understandably as 3D printers with a pricetag around 3 to 4 thousand Euro are not mainly sold to consumer. (Ultimaker. 2017)

Technological

This is about all developments and innovations an organization has to respond to in order to keep up with the times.

This year, according to Ultimaker VP Paul Heiden, it will be interesting to see if the concept of printerfarms will be embraced. Many parties are doing so, Stratasys with an entirely new concept. Ultimaker who do it more on a software level. (3D Print Magazine. 2018)
2018 zou zich wel eens kunnen ontpoppen tot het jaar waarin de groei van het aantal FDM printers in de maakindustrie versneld doorzet. Een jaar geleden schetsten we op dit punt als een van de 5 trends voor 2017 de komst van hoogwaardigere filamenten. Met name PEEK en PEI. Deze ontwikkeling is er inderdaad op gang gekomen. Het aantal FDM printers voor hoogwaardigere materialen is toegenomen. Maar mede doordat chemiebedrijven nadrukkelijk in additive manufacturing zijn gestapt, begint ook het 3D printen met andere kunststoffen momentum te krijgen. En daarmee steunen de materiaalproducenten de beweging van prototyping naar de productie die fabrikanten zoals Ultimaker willen maken. "We willen de stap van prototyping naar de productie van functionele onderdelen mogelijk maken", zegt Keith Cox Senior Business Manager Additive Manufacturing bij Sabic. "Het zal tijd nodig hebben, maar als we in dit tempo doorgaan, dan zal de adoptie van deze technologie sneller verlopen. Wij geloven dat AM een sterke toekomst heeft als conversieproces voor industriële onderdelen." In de eerste editie van 3D Print magazine kun je ook een interview met Kieth Cox lezen over de visie van Sabic op AM. Sabic heeft ondertussen een lijn van 6 hoogwaardige filamenten in de markt gezet. Daaronder Lexan EXL, een sterk polycarbonaat voor mogelijke toepassingen in de luchtvaartindustrie. (3D Print Magazine. 2018)

En tegen het eind van dit jaar komen de 5-assige FDM (3D Print Magazine. 2018) printers naar de markt. Ook dat opent weer nieuwe mogelijkheden. Het Poolse Verashape liet onlangs al een prototype van de machine zien. De 5-assige VShaper begint steeds meer op een CNC machine te lijken, want de fabrikant zet er een automatische wisselaar voor de 3D printkoppen in. De Oostenrijkse fabrikant Hage 3D kiest deels dezelfde richting. De Oostenrijkers bouwen de FDM printer op basis van Siemens aandrijftechnologie, gecombineerd met Sinumerik 848D Sl besturing. De stap van 3- naar 5-assig FDM printen is een interessante, omdat hiermee bij FDM printtechnologie supportmateriaal niet langer nodig wordt en door automatische printkopwissel het gebruik van meerdere materialen in één werkstuk mogelijk wordt. Aan de andere kant van het spectrum van FDM printen gebeurt ook het nodige. In de high end markt heeft Stratasys in 2017 een aerospace versie van de Fortus 900mc en 450 mc gelanceerd. Een toeleverancier in Hong Kong zet deze FDM printer met Ultem in voor het 3D printen van interieurdelen van vliegtuigen. Hiervoor zijn machine, materiaal en proces gecertificeerd. Ook het Spaanse Indaero gebruikt de Fortus 450 mc in combinatie met Ultem om direct interieurcomponenten te printen. Daarnaast wordt er tooling voor vliegtuigbouwers mee geproduceerd. Hiermee produceert Indaero onder andere voor Airbus. (3D Print Magazine. 2018)

As 3D printing technologies are maturing, the focus will turn towards streamlining pre- and post-production processes. While a large segment of 3D-printed production tools and prototypes are ready for use nearly straight out of the machine, with minimal finishing, there's also a huge number of end-parts that require complex finishing processes. This is not only labor-intensive, but also cost-intensive. (Materialise. 2018)

Industrial automation in the form of pick-and-place robotics has the potential to drastically raise efficiency by cutting post-production time and costs. Pair that with software know-how, and we envision an automated post-production system that ensures traceability and speed without over-reliance on manual intervention. Software will also increasingly play a role in the automation of pre-production steps, as illustrated by the surge in interest in simulation software, which is mostly driven by the rising adoption of Metal 3D Printing. While Metal 3D Printing has already proven its vast potential for time- and cost-savings,

APPENDIX J

the cost of wasted material due to build fails quickly becomes unaffordable and we expect simulation software will play an increasingly important role in predicting failures before they happen. (Materialise. 2018)

Integration

In the last few years we have seen 3D Printing claiming its position in supply chains. With faster lead times and tooling-free production, 3D Printing has proven to be a valuable technology for those applications that are traditionally resource-intensive. It also leads to leaner supply chains and fewer stock risks. We believe that 3D Printing will steadily increase its value in manufacturing supply chains in two ways: by enabling the creation of digital supply chains, which hold the promise of transforming entire business models, such as the hearing aid and eyewear industry; and by becoming more integrated in existing supply chains.

Collaboration

Collaboration is key to expanding 3D Printing to manufacturing industries. Increasing collaboration between existing players, such as hardware, software and service providers, will lead to optimized and easier-to-integrate product offerings, which will fuel adoption. We also expect to see more collaboration between the 3D printing industry and its customers. Co-creation, which creates a framework that allows for the integration of 3D printing software, engineering and manufacturing knowledge with a customer's specific market knowledge, is the real driver of innovation with transformative impact.

The statistic shows level of use for various applications of 3D printing, between 2015 and 2018. According to this latest survey, conducted in 2018, 41 percent professionals who use 3D printing said they did so to create proofs of concept. (Ultimaker. 2018)

84 % of companies surveyed for EY's Global 3D Printing Report 2016 reported using 3D printing for product development, with 38 % expecting that additive manufacturing would become a part of their production processes to create end-use items by 2021. (EY Global. 2016)

1. New Materials with Improved Properties

Many companies have released and are continuously developing composite materials for FDM. Most involve carbon fibers and are discussed in this review. Arevo Labs and Mark Forged are two of many companies that offer composite materials for higher performance, the table below lists their current offerings (CF = Carbon Fiber, CNT = Carbon Nano Tubes). Virtual Foundry are also working on developing a metal rich filament (with about 89% metal, 11% binder polymer), which they claim can be used to make mostly-metal parts for non-functional purposes using existing FDM printers and a heat treatment to vaporize the binder. In short, while ABS and PLA dominate the market, there is a wide range of materials commercially available and this list is growing each year. (Bhate, D. 2016)

Even with newer materials, a fundamental problem in FDM is the anisotropy of the parts and the fact that the build direction introduces weak interfaces. However, there are several efforts underway to improve the mechanical properties of FDM parts and this is an exciting space to follow with many approaches to this being taken. Some of these involve explicitly improving the interfacial strength: one of the ways this can be achieved is by pre-heating the base layer (as being investigated by Prof. Keng Hsu at the Arizona State University using lasers and presented at the RAPID 2016 conference). Another approach is being developed by a company called Essentium who combine microwave heating and CNT coated filaments as shown in the video below.

Taking a very different approach, Arevo labs has developed a 6-axis robotic FDM process that allows for conformal deposition of carbon fiber composites and uses an FEA solver to generate optimized toolpaths for improved properties.

Plastics or polymers are the major materials used for 3D printing. Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA), and polyamides are the major polymers that are used in both commercial as well as general applications. ABS and PLA are extensively used in the Fusible Deposition Modelling (FDM) technology in 3D printing; many patents related to this technology expired in 2008. Polyamides are used in powder form in the Selective Laser Sintering (SLS) technology; a majority of patents related to this technology expired in 2014. SLS is widely used in commercial practices and is expected to dominate the 3D printing market in terms of technology. Polyamides such as PA11 and PA12 are major polymers that can be used in powdered form. Major companies manufacturing PA11 and PA12 such as Arkema SA (France) and Evonik AG (Germany) have been largely instrumental in promoting these grades, along with major companies operational in the 3D printing market, including 3D Systems Corporations (U.S.), and EOS GmbH (Germany), among others. These factors are expected to boost the demand of polyamides as major 3D printing plastics in near future. (Duppaliwar, A. 2018)

APPENDIX K

List of requirements

Performance

- Decreases down-time (time in which the machine is not printing)
- Versatility
  - May not limit the current capabilities of FDM printing (e.g. different material usage and shapes built)
  - Ability to pause mid-print for embedded features
- Can be integrated within industrial product lines, without alteration of existing machines
- Certainty that print corresponds to digital files
- Increase success rate of prints
- Corresponds to and implements Ultimakers' material database
- Detection of failures (Quality control)
- Product complies with the SKG certificate
- Product complies with AM Standards (Appendix L)
- Indicate when operating
- Indicate when not in use
- Indicate any problems (No materials fed, part stuck, nozzle clogged) and assist in fixing them
- The product can be monitored remotely
- The product's functions can be tested on-site

Scalability

- Ability to be used on larger scale (higher part output) (Interconnection)
- Combine multiple printers (Interconnection)

Environment

- Communication (Interconnection)
  - Must be capable of communication with a central hub
  - Must be capable of communication with multiple other 3D printers
  - Must be capable of communication with other machines (e.g. robotics to remove prints/add spools)
  - Give feedback to the network (Digitization & Digitalization)
- Ability to make decisions (e.g. cancel prints, change temperatures, change Gcode) (Decentralized decision making)
- Adjustable/regulated temperature
- Minimize wasted plastics
- Can detect human operators in the vicinity, avoid hitting with moving parts
- The product complies to the norm EN-13241. The machine must be safe to operate unsupervised in the presence of people.

Installation

- Must fit in a production facility (Interconnection)
- Must communicate with human operators and give useful data (Information transparency)
- Must support human operators in what is expected (Technical assistance)
- Can be adjusted on site, to compensate for deviation in the height of the connection (+-100 mm)

Lifespan/Maintenance

- Used continuously
- Must monitor parts prone to wear
- Scheduled maintenance (Appendix M for maintenance on Ultimaker printers) (information transparency)
- Maintenance part within reach for a technician/robot
- Product has a minimal technical lifespan of 10 years with proper maintenance (as based on lifetimes of machinery and equipment, Azeez Eruban, A. 2019)
- The product has a 5-year warranty

Manufacturing costs

- New market where multiple manufacturers are trying to enter, more research is needed to find how far the price can stretch with added value
- Sales prices cannot exceed €10.000 euro per printing unit
- Production price cannot exceed €2.500

Reusability

- Modular design, as the industry is rapidly moving forward upgrades will quickly be available, to keep up with competition the machines must be capable of easy upgrades/updates
- The product is made from recyclable materials, no irremovable glue used in the product
- Components are replaceable

Software

- Automatically set the printing settings
- Interface for maintenance
- Support interface for designers
- Digital manual/interactive manual

APPENDIX K

Decrease human intervention/necessity in the process.

- Optimize model for process
- Creating/Uploading Gcode
- Selecting printer
- Preparing correct material
- Preparing printbed
- Monitoring Print
- Removing print
- Post-processing

Transport

- The product can be moved to the installation location by 1 truck (tractor-trailer)
- Installed and by a specialized mechanic

Packaging

- Protection against impact and water damage
- Fully assembled, per unit

Batch-size

- Produced on demand

Production facilities

- At Ultimaker facilities
- Sensors by external companies

Dimensions and weigth

- Max amount of noise
- Maximum dimensions

Materials

- Nen Norms

Product life span

- 15 Years lifespan (Erumban, A. 2008)
- Extend product lifespan by applying updates
- Extend product lifespan by applying upgrades

Norms and standards

- Safety indication (human operators may not come into contact with hot parts)
- Detect hazardous fumes
- Should be eligible for UL BlueCard (Industries.UL. 2019)

Operational certainty

- Error margin of maximum 10%
- Detect errors and resolve them
- May not have a fire hazard
- May not be able to fall over
- Moving parts out of reach of operators

Safety

- Fire and fume detection

Product policy

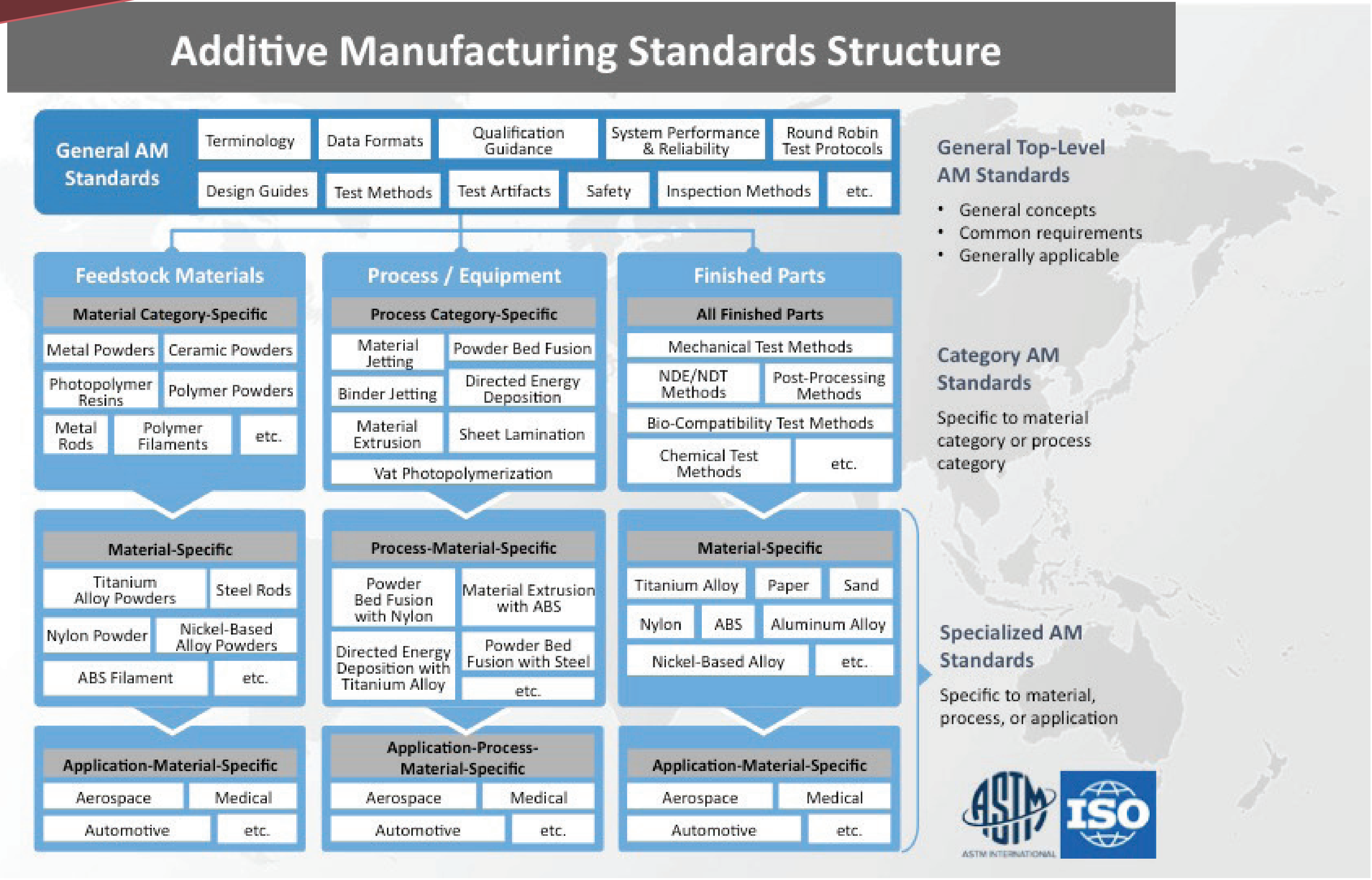
- Ultimaker is specialized in XYZ FDM printers, must fit with their capabilities

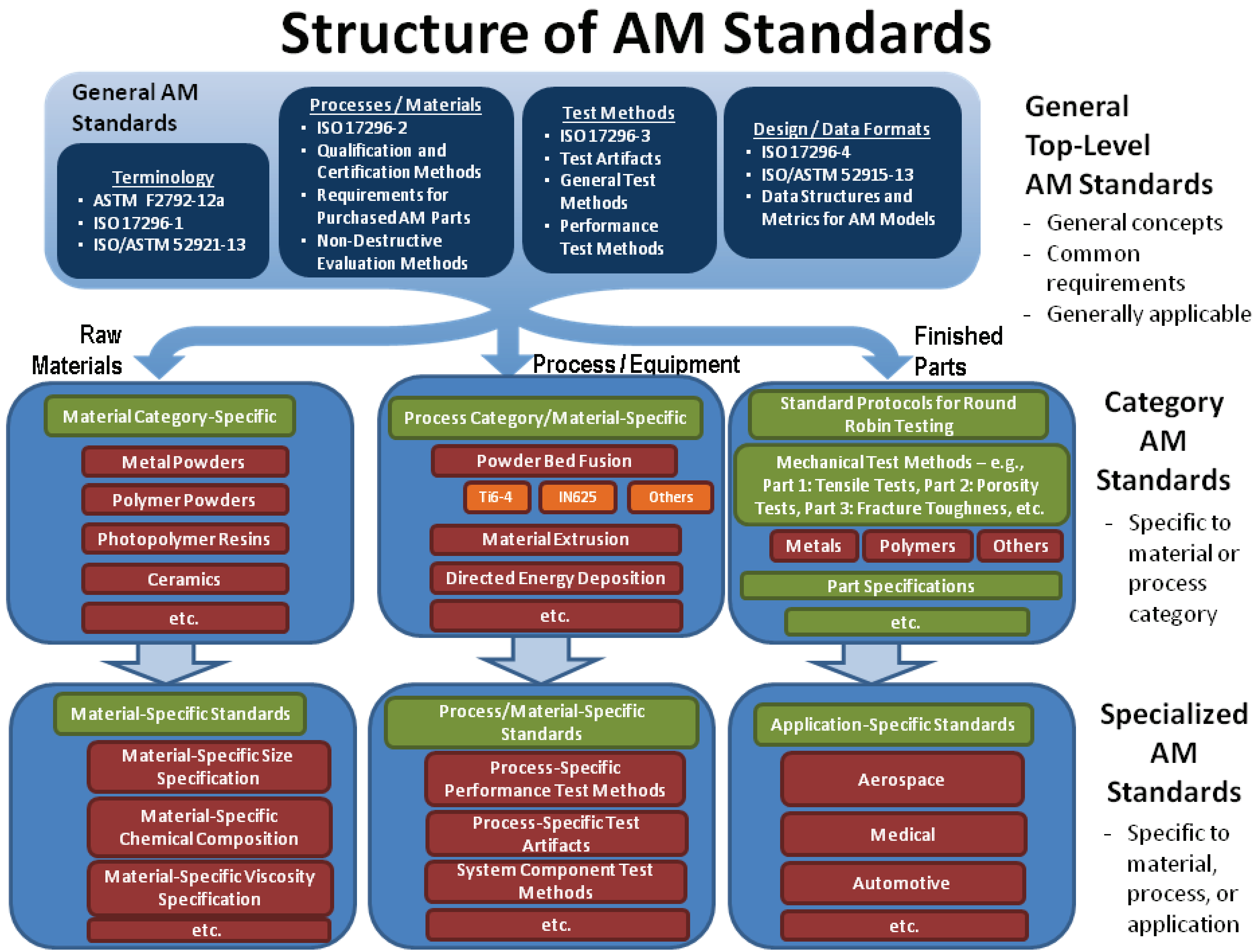
Product liability

- Must come with an agreement to waiver any flaws in produced parts

APPENDIX L

AM Standards





APPENDIX M

UM 5 Maintenance

6.3 Maintenance schedule

To keep your Ultimaker S5 in optimal condition we recommend the following maintenance schedule, based on 1,500 printing hours per year:

Every month	Every 3 months	Every year
Clean the printer Lubricate the axles (*)	Check for play on the axles Check tension of short belts Check for debris in front fan of print head Check quality of nozzle cover Lubricate lead screw Z motor Clean the feeders Clean the print cores	Lubricate the feeder gear Replace the Bowden tubes Clean system fans Lubricate hinges

(*) The X, Y and Z axles do not need lubrication for the first year of using the printer. After this, they should be lubricated monthly.

If the usage frequency is higher, we recommend performing more frequent maintenance on your printer to ensure optimal printing results.

6.4 Clean the printer

For the best print results it is important to keep the Ultimaker S5 clean while using it. It is advised to not use the Ultimaker S5 in a room where it can easily be covered with dust, and to remove small pieces of material that might be in the printer. Besides this, there are a few parts in the Ultimaker S5 that might require more regular cleaning.

Clean the glass/aluminum build plate

After printing, there might be print leftovers or excess glue stuck to the build plate. This can cause an uneven print surface. Potential sources of contamination are dust or fatty substances such as finger grease. Removing a print may also reduce the adhesion quality of a layer of glue. It is advised to regularly clean the build plate and reapply glue (if applicable).

Before starting a new print, always check the surface of the build plate. At least once a month, clean the build plate thoroughly by taking the following steps:

Always make sure that the build plate has cooled down and is lowered to the bottom of the Z axis.

1. Open the build plate clamps at the front, slide the glass or aluminum build plate forward, and take it out of the printer.
2. Use lukewarm water and a non-abrasive sponge to clean the build plate and to remove any adhesives. If necessary, some detergent can be used to remove adhesives, or alcohol gel can be used to get rid of any fatty substances.
3. Dry the build plate with a clean microfiber cloth.
4. Place the glass or aluminum build plate on the heated bed with the warning sticker facing upwards. Ensure that it snaps into the build plate clamps at the back and close the build plate clamps at the front to secure it.

Clean the glass components

All glass components of the printer (the glass doors and touchscreen) should be cleaned regularly to remove dust or fingerprints. They can be cleaned by using a dry, or if necessary, a somewhat moist microfiber cloth.

Clean the nozzles

While using the Ultimaker S5, material can get stuck to the outside of the nozzles and degrade. Although this will not damage your printer, it is recommended keep the nozzles clean in order to achieve the best print results.
Before starting a new print, always check the nozzles. At least once a month, remove the plastic from the outside of the nozzles by taking the following steps:

During this procedure do not touch the nozzles and be careful while cleaning them as they will become hot.

1. On the Ultimaker S5, navigate to the configuration menu, select *print core 1*, then click on the icon in the top-right corner and select *Set temperature*.
2. Use the controls to set the target temperature to 150 °C. Repeat this for print core 2 and make sure this print core is lowered.
3. Wait for the material on the outside to get soft. When the nozzles are hot, carefully remove the material with tweezers.

The nozzle cover is fragile and has a sealing function. Be careful not to damage the nozzle cover when using tweezers.

Material may have accumulated higher up on the outside of the nozzle, above the nozzle cover. Check if this is the case by opening the print head fan bracket. To ensure the print head can close smoothly, this material should be removed using tweezers, as described above.

Clean the Bowden tubes

Particles in the Bowden tubes can impede smooth movement of the filament, or mix colors. Clean the Bowden tubes at least once a month, or after experiencing an issue with filament grinding. To clean the Bowden tubes, they must first be removed from the printer.

1. Start by removing the material. Go to the configuration menu, select the material you want to remove and then *Unload*. After this, turn off the printer.
2. Place the print head in the front-right corner.
3. Use your fingernail to remove the clamp clips from the tube coupling collets at the print head and feeders.
4. Press down on the tube coupling collet in the print head and at the same time, pull the Bowden tube upwards, out of the print head. Repeat these steps for the feeder.

The cable clips that hold the second Bowden tube to the print head cable do not have to be removed, you can leave them in place.

5. Cut off a small piece of sponge or ball up a piece of tissue.
6. Insert this into the feeder end of the Bowden tube and push it all the way through the tube with a length of filament. Do this for both Bowden tubes, using a clean piece of sponge or tissue for each.

To clean the tube most efficiently, make sure the sponge or ball of tissue is a tight fit inside the Bowden tube. Note that if it is too big it will be difficult to push through.

7. Insert the Bowden tube into the feeder by pressing down on the tube coupling collet in the feeder and pushing the Bowden tube all the way in. Secure the tube with the clamp clip. Repeat this for the other Bowden tube.

Pay attention to the orientation of the first Bowden tube that was completely removed from the printer. One side is chamfered for easier entry of the filament; this side should be inserted into the feeder.

8. Insert the Bowden tube into the print head by pressing down on the tube coupling collet in the print head and pushing the Bowden tube all the way in. Secure the tube with the clamp clip. Repeat this for the other Bowden tube.

Inside of the printer

Small pieces of material can gather inside the printer, such as priming blobs. Remove these regularly from the inside of the printer by taking the following steps:

1. Raise the build plate by navigating to *Configuration* → *Build plate* and select *Raise*.
2. Clean the inside of the printer with a microfiber cloth or vacuum cleaner. Pay extra attention to the area around the Z limit switch as obstructions here can cause print problems.

Leaving larger objects on the bottom panel can lead to errors, as they prevent the build plate from homing properly.

6.5 Lubricate the axles

To make sure that your print head and Z stage can move smoothly at all times, it is advised to lubricate the axles every month after the first year of printing. If the axles feel dry, this can show in your prints as small ridges on surfaces. Apply some oil to the axles at least once a month.

A bottle of oil is included in the accessory box of your Ultimaker S5. This oil is specifically for the smooth axles of the Ultimaker S5. Only use the supplied oil, as using other oils or grease may affect the coating of the axles, which can affect the performance of your Ultimaker S5.

X and Y axles

Apply a small drop of oil to each of the X and Y axles as well as both print head shafts. Manually move the print head around to evenly distribute the oil.

Do not apply too much oil to the axles, as it might drip from the axles on to the build plate, which will affect print adhesion. If a drop of oil does fall on the build plate, make sure to clean it thoroughly before printing.

Z axles

Apply a small drop of oil to each of the Z axles. In the Ultimaker menu, go to *Configuration* → *Build plate*. Select *Raise* and then *Lower* to move the build plate up and down in order to evenly distribute the oil.

APPENDIX M

6.6 Check for play on the axles

The four X and Y axles are locked in place by the pulleys. However, it is possible that one or more of the pulleys can become slightly loose over time, which could affect their alignment. If this is the case, there could be play on the X and/or Y axles which can cause issues with print quality.

It is recommended to check for play on the axles at least once every three months.

Start with the right X axle. Place the print head in the back-left corner of the printer to keep it out of the way. Hold the frame of the Ultimaker S5 with one hand, and firmly hold the right X axle with the other. Attempt to move the axle forwards and backwards; do not be afraid to apply too much force.

Repeat this for the other axles. Make sure to move the print head to the opposite side each time.

The axles should not move at all. If one of the axles does move, you will notice a ticking noise caused by the pulleys hitting the frame. In this case, it is recommended to calibrate the print head. For instructions on how to do this, take a look at the Ultimaker website.

6.7 Check the tension of the short belts

Maintaining correct tension on the short belts is important to ensure good print quality. The short belts transfer the movements of the X and Y motors to the print head. If the belts are too loose, print head movement may not be accurate, which can cause print inaccuracies.

Over time, the belts may become slack. It is recommended to check the tension of the short belts at least once every three months.

Pluck the two short belts to check their tension. They should resonate, like a guitar string. It should not be possible to press the belt against itself. Furthermore, the tension of the two belts should be equal.

To restore the tension, perform the following steps:
1. Loosen the Y motor by using the hex screwdriver to loosen the four bolts that hold the Y motor to the left panel. Do not remove the bolts, but the motor should be able to slide up and down.
2. Firmly press down on the motor with one hand. This ensures maximum tension on the short belt.
3. While still pressing the motor down, tighten the four bolts of the Y motor in a cross pattern. First tighten the top-left bolt, then the bottom-right, next the bottom-left and ending with the top-right. This ensures that the motor is attached straight.
4. Perform the above steps for the X motor that is attached to the back panel. Afterwards, check the tension of both belts again.

6.8 Check for debris in the front fan of the print head

The front fan cools the print cores during a print. This helps to prevent the heat from the nozzle traveling too far upwards.

The fan takes in air from the front of the print head and directs it towards the print cores. Sometimes the airflow causes thin strands of filament to be sucked into the fan during a print. If strands accumulate in the fan, they can decrease the effective cooling and eventually obstruct the fan and prevent it from spinning. Especially high-temperature materials, such as CPE+, PC, and ABS are sensitive to this.

To check the front fan, first gently open the front fan bracket. Blow into the front fan to see if it spins smoothly. If it does not move at all, or stops spinning abruptly, carefully clear any obstructions from the front fan with some tweezers.

⚠ Make sure that the print cores are completely cooled and the printer is turned off before performing this check.

ℹ Some filament debris can also be visible from the outside of the print head. Make sure to remove this too.

If the fan is still not spinning after removing visible filament debris, it should be replaced.

6.9 Check the quality of the nozzle cover

The nozzle cover shields the print cores from cold airflow from the fans, which helps the print cores to maintain a stable temperature while printing. The cover also helps to prevent backflow of material into the print head when something goes wrong during printing.

The heat of the nozzles may cause wear on the nozzle cover over time. It is recommended to check the quality of the cover at least once every three months. The accessory box of the Ultimaker S5 contains three spare nozzle covers.

Examine the bottom of the print head to see if the holes where the nozzles come through are still round and the cover still forms a good seal. Also gently open the fan bracket to check the other side of the nozzle cover.

If the nozzle cover looks like it needs to be replaced, please follow these instructions.

Remove the old cover

1. First, remove both print cores by going to the configuration overview and selecting *Unload* for both print cores.
2. Close the print head fan bracket, and manually place the print head in the front center of the printer.
3. Peel away the front corner of the nozzle cover, and pull it out of the print head fan bracket.

Place the new cover

1. Open the print head fan bracket.
2. Take the new nozzle cover and hold it in the correct orientation behind the print head fan bracket. Make sure the protruding shapes of the cover match the shapes of the holes in the bracket.

3. Insert the middle tab of the nozzle cover through the slot in the print head fan bracket. From the inside of the print head, apply pressure to the metal plate. At the same time, pull the tab through the bracket and plate until the seal locks the cover in place.

ℹ Use flat tip or round tip tweezers to pull the tab through the metal plate. This makes this action easier, as the tab may be difficult to reach by hand.

4. Pull the right side of the nozzle cover, fold the pocket over the edge of the metal plate, and push the silicone tab under the metal tab of the print head fan bracket. Repeat this for the left side.

5. Push the front tab through the slot in the print head fan bracket, while applying pressure to the metal plate from the inside of the printer. Make sure the seal is pushed through the plate, to lock the cover in place.
6. Close the print head fan bracket and check if the new nozzle cover is correctly placed. Slide your finger across the bottom of the print head. If the nozzle cover easily detaches from the fan bracket, it is not correctly placed. Follow steps 3 - 5 again.

⚠ If the nozzle cover is not placed correctly, it may get caught on the print. This could cause the fan bracket to open during printing.

7. Insert both print cores, following the guide in the configuration menu.
8. With the front fan bracket closed, hold the nozzle cover at both sides and slightly move it left and right. The metal place and nozzle cover will now align themselves with the print cores.

The nozzle cover should not easily detach from the fan bracket

ℹ It is recommended to check the placement and alignment of the cover by manually lifting and lowering the second print core. To do this, move the lift switch on the right side of the print head. Check if the fan bracket remains closed as the second print core is lowered.

6.10 Lubricate the lead screw of the Z motor

The lead screw is connected to the Z motor and controls the movements of the Z stage. To ensure smooth movement of the Z stage, it is recommended to periodically apply grease to the lead screw.

Over time, grease may need to be reapplied to maintain consistent and accurate movement of the Z stage. A tube of grease is included in the accessory box of your Ultimaker S5.

1. Make sure that the build plate is positioned at the bottom of the Ultimaker S5.
2. Apply a small amount of grease to the lead screw of the Z motor.
3. In the Ultimaker menu, go to *Configuration* → *Build plate*.
4. Select *Raise* and then *Lower* to move the build plate up and down to evenly distribute the grease.

ℹ Only use the grease on the lead screw of the Z motor.

APPENDIX M

6.11 Clean the feeders

The feeders forward filament to the print head. To make sure that exactly the right amount of material is extruded, it is important that the feeder gears can turn smoothly.

After many hours of printing, or when material has been ground down, there is a chance that there are small filament particles in the feeders. It is recommended to clean the inside of the feeders after three months. In order to do this, the feeders have to be removed from the printer.

The following steps need to be performed for both feeder 1 and feeder 2:
1. Start by removing the material. Go to the configuration menu, select the material you want to remove and then *Unload*. After this, turn off the printer and remove the power cable.
2. Remove the clamp clip from the feeder-end of the Bowden tube, press down on the tube coupling collet and pull the Bowden tube upwards out of the feeder. Next, remove the tube coupling collet.
3. Reduce the tension of the feeder by turning the bolt in the top of the feeder with the hex screwdriver, until the indicator is completely at the top.


4. Use the hex screwdriver to loosen the four bolts of the feeder housing.
5. Carefully pull the front part of the feeder away from the printer and put it aside.

Be careful not to lose the ring that is located at the bottom of the feeder. If it falls out, place it back in the feeder housing with the widest side at the top.

6. Use a small brush to gently clean all filament particles from the knurled wheel, the flow sensor axis, and the inside of the feeder housing.
7. Place the front part over the feeder again and firmly push it into place. Insert the four bolts and tighten them in a cross pattern, starting in the top-left corner.
8. Insert the tube coupling collet into the feeder and push the Bowden tube all the way in. Secure the tube with the clamp clip.
9. Reset the tension of the feeder by turning the bolt in the top of the feeder, until the indicator is at the middle mark.


6.12 Clean the print cores

Maintenance of the BB print core should be performed once every three months. Using the Ultimaker cleaning filament is the most effective way to clean and unclog the BB print core on the Ultimaker S5. If you don't have the Ultimaker cleaning filament at your disposal, you can use PLA instead.

Cleaning filament can be used to clean the print core on an Ultimaker S5 by applying hot and cold pulls. Hot pulls are used to get the biggest parts of degraded material out of the print core and are especially necessary when a print core is clogged. With a cold pull, the remaining small particles will be pulled out, ensuring the print core is completely clean.

If necessary, you can also use this method to clean an AA print core.

Preparation

1. Go to *Preferences* → *Maintenance* → *Print head* → *Print core cleaning* and select *Start* to start the cleaning procedure.

The print head will move to the front-right corner to prepare itself.

2. Select the print core you want to clean: *print core 1* or *print core 2*.
3. Select the material you want to use for cleaning: *Cleaning filament* or *PLA filament*.
4. Wait for the printer to heat up the print core and to retract the filament until its end is visible in the Bowden tube.

If the material is not retracted there is a chance that the material has been ground down and is stuck in the feeder. In this case, remove the material manually as described in the troubleshooting section on the Ultimaker website.

5. Remove the Bowden tube from the print head. First, remove the clamp clip and then push down on the tube coupling collet while pulling the Bowden tube upwards, out of the print head. *Confirm* to continue.


Hot pull

1. Insert the filament (Ultimaker cleaning filament or PLA) into the print head until you feel some resistance.
2. Hold the filament with pliers and gently apply pressure to the material for ±1 second so that it extrudes from the print core or until it cannot be pushed any further, and directly pull the filament out with a quick, firm pull.

Use pliers to prevent injuries to your hands in case the material breaks.


3. Cut off the tip of the filament that you have just pulled out.
4. Check the color and the shape of the tip of the filament and compare it with the image below. The goal is to have a clean tip.

5. Repeat this procedure until there is no more degraded material visible on the tip of the cleaning filament. The tip of the filament should look as clean as the example on the right.
6. Once the tip of the filament is clean, manually flush some filament through the print core with pliers and take it out again. *Confirm* to continue.

Cold pull

1. Insert the filament (Ultimaker cleaning filament or PLA) into the print head until you feel some resistance.
2. Hold the filament with pliers and gently apply pressure to extrude some material. *Confirm* to continue.
3. Maintain pressure on the filament with the pliers for the duration of the progress bar.
4. Release the filament and wait until the print core has cooled down.
5. Grab the filament with pliers and pull it out with a quick, firm pull. *Confirm* to continue.


6. Take a look at the tip of the filament and see if it has a clean, cone-shaped tip like shown on the example to the right. *Confirm* to continue.

If the tip of the filament is not clean, go back to hot pull or cold pull to repeat the cleaning steps.


Reassembly

1. Insert the Bowden tube into the print head and secure with the clamp clip. *Confirm* to continue.
2. Wait for the Ultimaker S5 to finalize the cleaning procedure.


6.13 Lubricate the feeder gear

To ensure that the feeders forward the filament smoothly and accurately, the gears are lubricated. After many hours of printing, it is recommended to reapply this lubrication. As small filament particles may have stuck to the gears, it is advised to clean them first.

It is also recommended to replace the Bowden tubes after one year. While lubricating the feeder gears, follow the instructions to replace the Bowden tubes simultaneously.

The following steps need to be performed for both feeder 1 and feeder 2:
1. Start by removing the material. Go to the configuration menu, select the material you want to remove and then *Unload*. After this, turn off the printer and remove the power cable.
2. Remove the clamp clip from the feeder-end of the Bowden tube, press down on the tube coupling collet and pull the Bowden tube upwards out of the feeder.
3. Use the hex screwdriver to loosen the two bolts that hold the feeder to the back panel.
4. Carefully move the feeder away from the back panel and disconnect the filament detection cable from the flow sensor.


5. Use a clean cloth or a cotton swab to wipe all filament particles and grease residue from the feeder gears. Clean both the gear connected to the motor and the larger gear inside the feeder.
6. Apply a small amount of grease to the gear attached to the feeder motor. There is no need to spread this out; the feeder will do this automatically when it turns.
7. Hold the feeder close to the back panel and connect the filament detection cable to the flow sensor.
8. Place the feeder back on the printer and secure it with the two bolts.
9. Insert the Bowden tube into the feeder by pressing down on the tube coupling collet in the feeder and pushing the Bowden tube all the way in. Secure the tube with the clamp clip.


6.14 Replace the Bowden tubes

The Bowden tubes guide the filament from the feeders to the print head.

Forwarding improperly cut or ground down filament through the Bowden tube could scratch or damage the inside of the tube. If this happens, the filament can no longer be forwarded to the print head smoothly. This can lead to under extrusion or other print quality issues.

After removing a Bowden tube multiple times, the tube coupling collet can wear out. If this happens, the tube coupling collet will no longer have a firm hold on the Bowden tube. In this case, the Bowden tube will move up and down during prints, which can negatively impact print quality.

If the Bowden tubes are permanently damaged, they need to be replaced. To maintain optimal print quality it is recommended to replace the Bowden tubes every year.

Disassembly

1. Start by removing the material. Go to the configuration menu, select the material you want to remove and the *Unload*. After this, turn off the printer.
2. Place the print head in the front-right corner.
3. Use your fingernail to remove the clamp clips from the tube coupling collets at the print head and feeders.
4. Press down on the tube coupling collet in the print head and at the same time, pull the Bowden tube upwards, out of the print head. Repeat these steps for the feeder.
5. When removing the Bowden tube from Extruder 2 (right), loosen the four cable clips from the Bowden tube to remove it completely.


APPENDIX M

Reassembly

1. Take the new Bowden tube and note the two different sides. The side which is chamfered should be inserted into the feeder. This allows easier access of the filament into the Bowden tube. The flat side should be inserted into the print head.
2. Insert the Bowden tube into the feeder by pressing down on the tube coupling collet in the feeder and pushing the Bowden tube all the way in. Secure the tube with the clamp clip.
3. Insert the Bowden tube into the print head by pressing down on the tube coupling collet in the print head and pushing the Bowden tube all the way in. Secure the tube with the clamp clip.
4. When replacing the Bowden tube from Extruder 2 (right), click the header cable clips onto the Bowden tube. Equally divide the clips over the Bowden tube.

6.15 Clean the system fans

The system fans are positioned at the back of the printer and need to be cleaned once a year.
This can be done by blowing into the fans in order to get small filament particles out. If necessary, an air blower or compressor can be used instead.

6.16 Lubricate the hinges

To make sure the glass doors will open and close smoothly, the hinges of the glass doors have to be lubricated once a year. This can be done by putting a small drop of oil in the top hole of each hinge.

7.3 Print quality issues

Poor build plate adhesion

When you experience problems with the adhesion of a print to the build plate, the following actions can be performed:
- Ensure that the correct material settings and adhesion method were used (see chapter 5.2 Materials).
- Recalibrate by using the detailed active leveling mode (see chapter 5.8 Calibration).
- Check the Ultimaker Cura settings that were used, and try printing with one of the default Ultimaker Cura profiles.

Grinding PVA

Typically incorrect handling or storage of the material can lead to grinding of the material. PVA should be printed and stored at a low humidity to avoid problems while printing. We advise a humidity below 50% for storage and below 55% while printing. It is also recommended to keep the ambient temperature below 28 °C while printing. In a standard air conditioned office, this humidity and temperature should be easy to achieve.

When PVA is ground down by the feeder, there are three main causes.
- **Incorrect storage** PVA is a material that absorbs moisture relatively easily and therefore storing it correctly (resealable bag, with humidity below 50%) is important. If PVA absorbs too much moisture it will get soft and malleable/pliable and in some cases even sticky. This can cause problems in the feeder as it might not be able to forward the PVA properly anymore. If this happens you can dry the PVA.
- **Coated Bowden tube** The Bowden tube can get coated on the inside due to incorrect printing conditions (mainly high humidity). If the humidity of the printing environment is too high (above 55%) and temperature is too high (above 28 °C) PVA might not be able to move easily through the Bowden tube. A solution for this is to clean the Bowden tube and dry it very well.
- **Clogged print core** High humidity can affect PVA quality, and lead to clogs in the print core. As a consequence, filament might get jammed, causing grinding in the feeder. When this happens, the print core should be cleaned by following the procedure described in chapter 6.11 Clean print cores.

For more information on how to resolve grinding issues, you can take a look at this page.

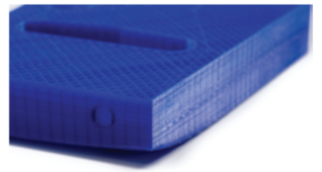
Under-extrusion

In simple terms, under-extrusion is when the printer is unable to supply a sufficient amount of material. Your Ultimaker S5 is under extruding when you see missing layers, very thin layers, or layers that have random dots and holes in them.

Under-extrusion can have several causes:
- Use of low quality material (diameter inconsistency) or wrong settings
- Feeder tension not set correctly
- Friction in the Bowden tube
- Small particles of material in the feeder or Bowden tube
- A partial clog in the print core

If your Ultimaker S5 is affected by under–extrusion, it is advised to take a look at this page for detailed troubleshooting instructions.

Warping



Warping occurs due to material shrinkage while printing, causing the corners of the print to lift and detach from the build plate. When plastics are printed, they firstly expand slightly but contract as they cool down. If material contracts too much, this causes the print to bend upwards from the build plate.

When your print is warping, ensure you have done the following:
- Use the active leveling to level the build plate
- In case of a glass build plate, apply a thin layer of glue
- Use the correct temperature and other settings as in the default Ultimaker Cura profiles
- Adjust the shape of your model according to the design guidelines described on www.ultimaker.com/3D-model-assistant.
- Use another material that is less prone to warping

To troubleshoot this issue in more detail, take a look at the Ultimaker website.

APPENDIX N

N

Design Directions

Human

->Co-creation results in a more authentic relation with the product – Jo Geraedts
DD: How can the industry benefit from co-creation

->Increasing amount of 3d printers among people – Sculpteo
DD: Explore a way to use the increasing knowledge and experience

Triggers

->FDM can replace traditional production methods – Peter Brier
DD: What are parallels between FDM printing and other production methods, where can it replace those?

->Some parts can gain a better material performance with the help of FDM printing – Ernst A. Poppe
DD: What geometries can benefit from being produced by FDM printing

->New applications are needed to spark the interest of the industry – Ruud Ruizenaar
DD: What new applications can be introduced for companies by using FDM

Smart Machines (Proces automation)
-> Finishing is labor and cost intensive – Duncan Maagdenberg
DD: How can product finishing be automated/streamlined?

-> Can (cheap) metrology be integrated in a 3d-printer – Duncan Maagdenberg
DD: Explore how to scan a printing process

-> 3D printing is too labor intensive – Rutger Schönfeld
DD: How do you decrease human necessity in FDM printing?

-> Removing support is annoying and takes a lot of effort – Sander Verhage
DD: Improve the process of support removal

-> Most prints fail in the first layer – Rutger Schönfeld, Sander Minnoye
DD: Find the possibility of direct monitoring of first layer

-> Industrial automation in the form of pick and place robotics drastically raises the process efficiency – Depest
DD: How can a pick and place robot interact with the system

-> A core principle of Industry 4.0 is Decentralized decision making
DD: What is needed for FDM printers to make simple decisions on their own? What are those decisions?

Organization/planning

-> Downtime causes huge delays in manufacturing processes –
DD: how to implement planned maintenance in the industry 4.0 workflow

Interaction with the system (topology optimization) (Digital Twin)

-> Increasing amount of filament materials are available for Ultimakers – Paul Heiden
DD: How to connect the right material to the needed properties

-> Simulation software will play a role in predicting failure before it happens – Depest
DD: What kinds of failure can be identified by the software

-> There is a difference between the original file and the print –
DD: How can the differences be identified and prevented?

-> FDM-printing can be hard to understand (overwhelming) for new users – Tjapko Vermeulen
DD: How can the bar be lowered for unexperienced users

-> Printers are increasingly being used for the production of custom tools used in the industry – Bas van Deursen
DD: Explore how to improve the production of tools for the industry, the user works together with the computer to optimize the design (topology optimization)

-> An Ultimaker contains thousands of settings for each print job. – Ruud Ruizenaar
DD: How to select the right settings for the application that is demanded of the product

-> There is a demand in functional use of printer settings – Ruud Ruizenaar
DD: How can a designer print his part easily with his specific (desired) features.

APPENDIX O

Creative Facilitation Session

Program:

ICEBREAKER

- Vertel wat je ontbeten hebt en vertel waarom dit typisch jou is.

- gebruikte items:

- doel: opening up. Zorgen dat iedereen een keer aan woord is geweest om zo verbale omgang te versoepelen en voor zover nodig de groepsdynamiek verbeteren (op luchtige manier)

- Schets je buurman als object en leg uit waarom je het ontwerp gekozen hebt

- gebruikte items: A4 + stiften

- doel: gebruik van schetsen normaal maken (iederen kan tekenen), creativiteit en inbeeldingsvermogen vergroten. Mensen aan woord laten -> in de hoop dat mensen makkelijker dingen durven te zeggen.

BRIEFING

- Leg kort uit waar de brainstorm over zal gaan.

- gebruikte items: niets, volledig verbaal

- doel: introduceren van het probleem zonder mensen op te zadelen met te veel details die belemmerend kunnen werken voor de creativiteit

ANALYSE

- 'flipover shout' 4de industriele revolutie

- gebruikte items: flipover vel + markers

- doel: de term is niet voor iedereen bekend en misschien denken mensen hierbij aan iets anders. Door iedereens gedachte leeg te schrijven komt iedereen op eenzelfde niveau qua definitie.

- flipover shout 3d printen

- gebruikte items: flipover vel + markers

- doel: Hierbij vooral gefocused op persoonlijke ervaring

-> emoties. kijken of dez overeen komen en hoe deze zijn gevormd

CHALLENGE FORMING

- doemdenken (worst case scenario)

- gebruikte items: flipover + markers

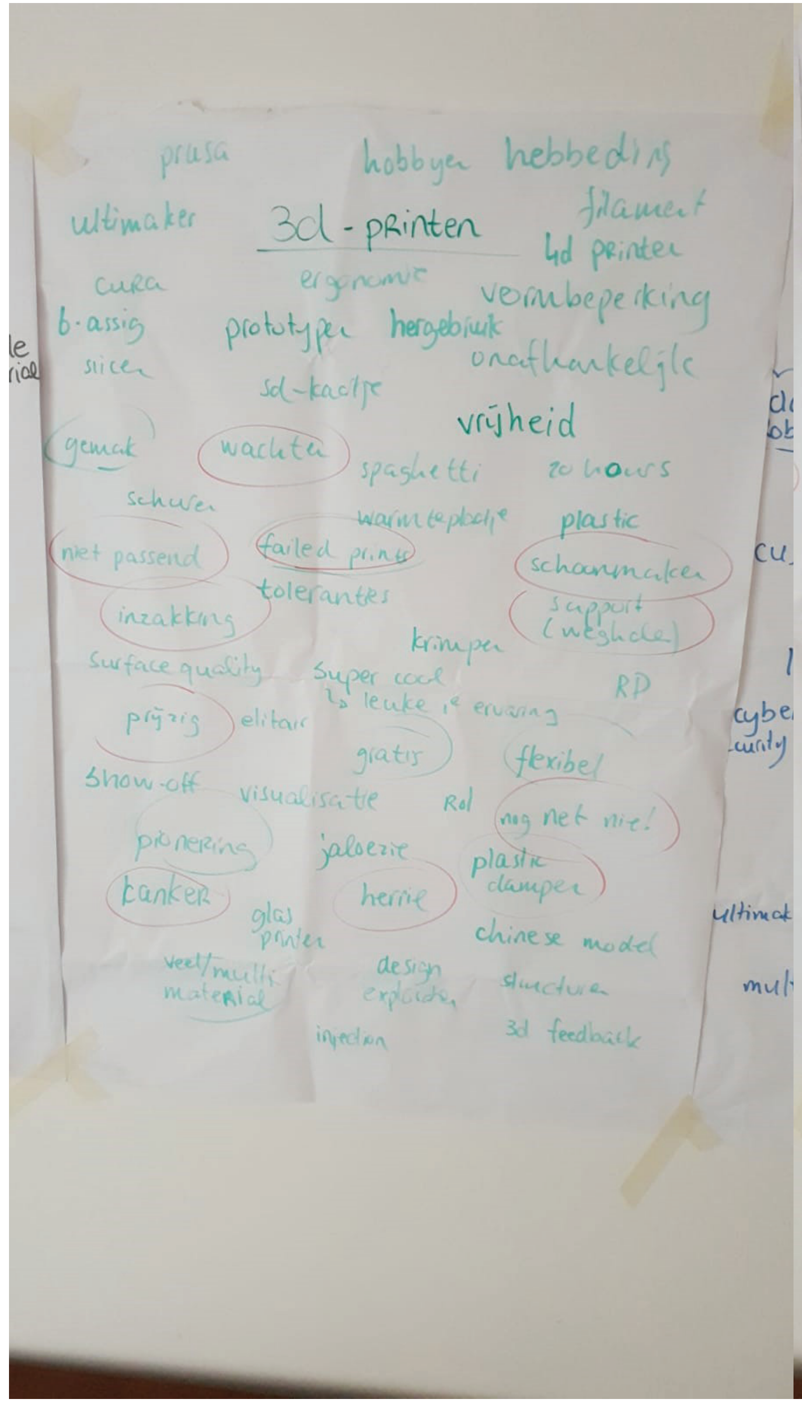
- doel: denken aan alles wat in het systeem zit. Doemdenken is een leuke en luchtige manier om over problemen na te denken. Door mensen een 'personage' te geven proberen meer kanten van het probleem te belichten.

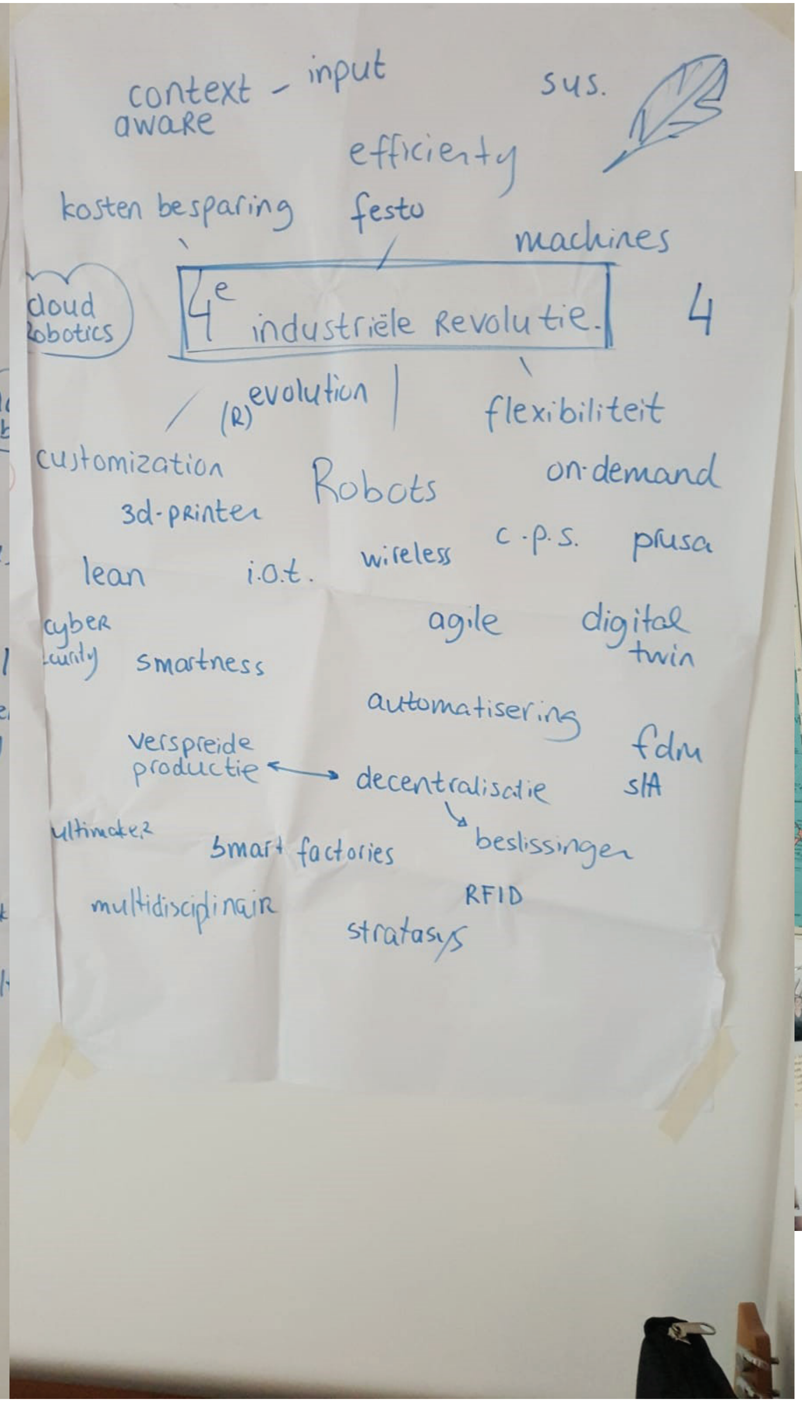
- 'design perfect system'

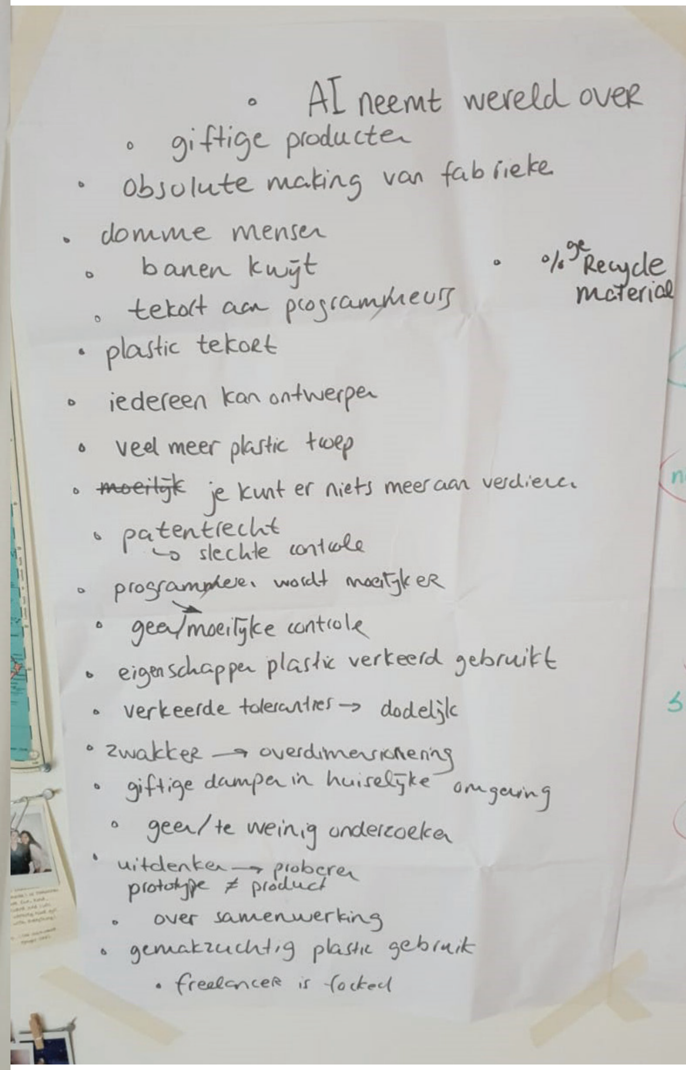
- gebruikte items: flipover + markers

- doel: alle eerste ideeen van je afschrijven om zo je gedachte leeg te maken voor het brainstormen + tevens samen een soort programma van eisen opstellen.

- 1-2-4 methode -> forming of design challenge







APPENDIX O

- gebruikte items: stiften, post-its

- doel: iedereen schrijft eerst zijn eigen visie op; zo zorg je ervoor dat uiteindelijk iedereen het met de visie een is. -> het word een kind van de gehele groep'. Door elkaar 'om te praten' naar elkaars visie kun je in debatvorm breder over het probleem nadenken.

BRAINSTORMING

- Vanuit challenge en 'programma van eisen' HKJ's opstellen

- gebruikte items: flipover + marker

- doel: scoping of the brainstorm. Laat eerst iedereen zijn zegje doen, convergeer daarna (mede door dot-voting) tot 5 hkj's

ENERGYZER

- Menselijke knoop

Korte oefening om even van je stoel te komen en groepsdynamiek te verbeteren

- Blind pictionary op een leuke manier het schetsen opnieuw benaderen. Laten zien in spelvorm dat iedereen kan schetsen & aanmoedigen dit in de brainstrom toe te passen. + vergroting visueel denken en creatief denken.

- Brainwriting

- gebruikte items: random stimuli: personages, random woorden, 'grabbelton'

- doel: ideeen genereren

CLUSTERING

- Probeer indien wenselijk overlappende ideeen samen te voegen

- gebruikte items: markers

- doel: Convergeren + maak de zee van ideeen wat overzichterlijker

IDEA SELECTING

- gebruik dot voting voor het selecteren van de meest relevante ideeen. -> lees expliciet de design challenge nog een keer voor om mensen op hetzelde pad te brengen.

- gebruikte items:

- doel: idea forming

CONCEPT FORMING

- Maak twee groepen. problem owner in groep van 3 (belangenverstrengeling)

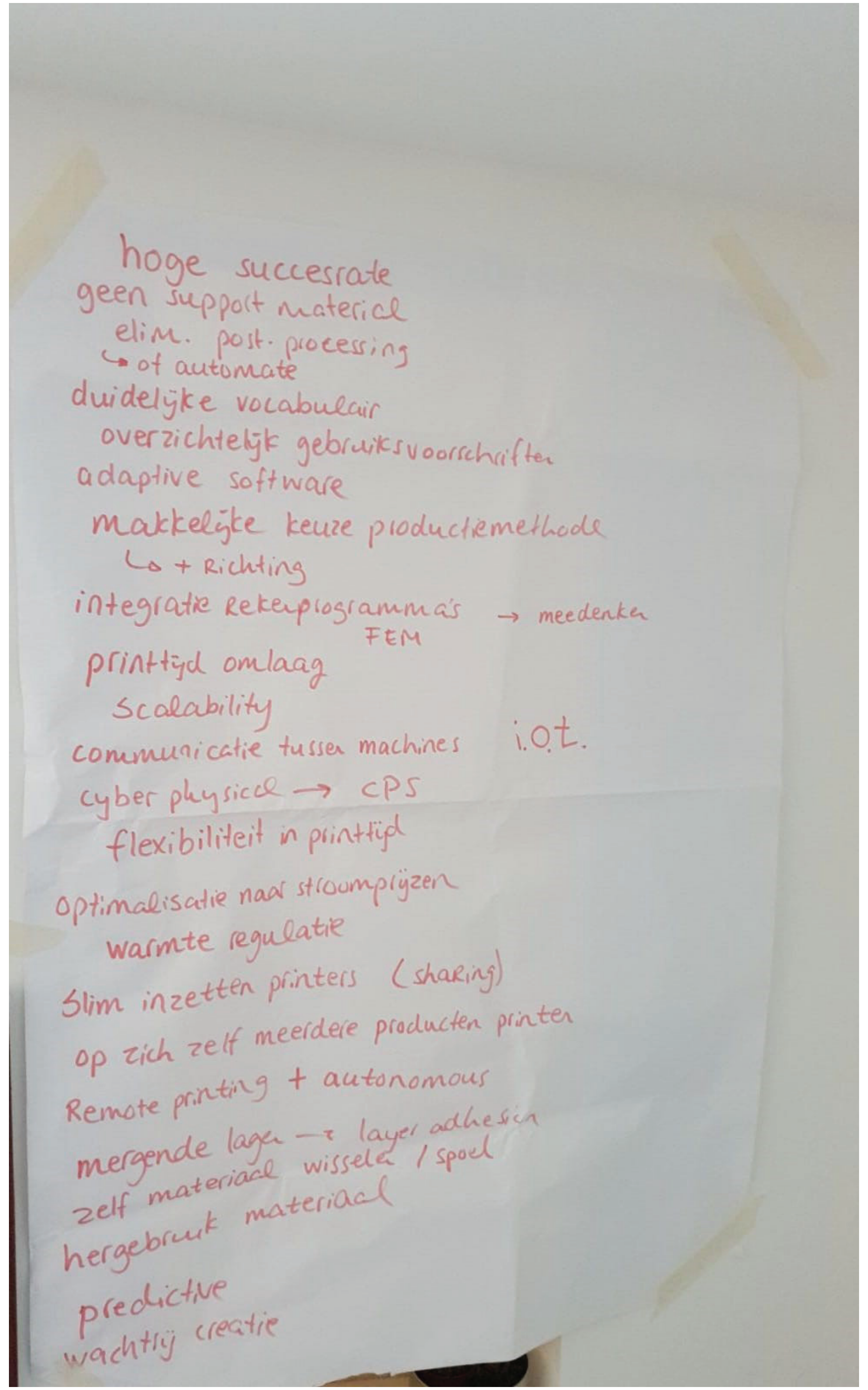
- gebruikte items: flipover + markers

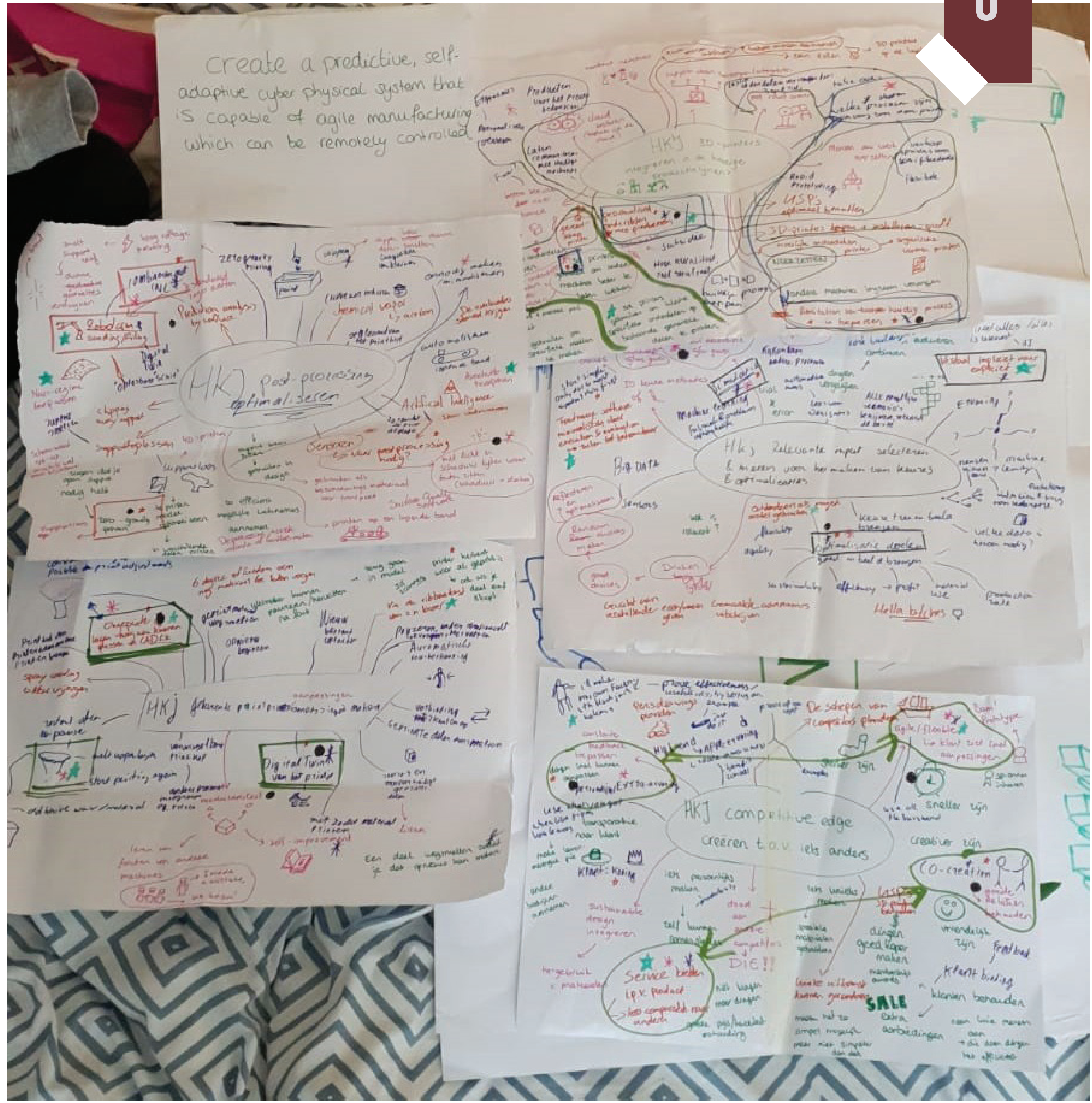
- doel: denk dieper na over de gekozen richtingen, wat zijn de haken en ogen aan de beoogde ideeen? 'kaf van koren scheiden'

- PRESENTATION

- gebruikte items: flipover + markers

- doel: verdedig je gekozen ideeen. Door kritiche vragen te stellen kun je ideeen nog een beetje scopen waar nodig. Maak het snel visueel omzo na te denken over het gehele systeem.

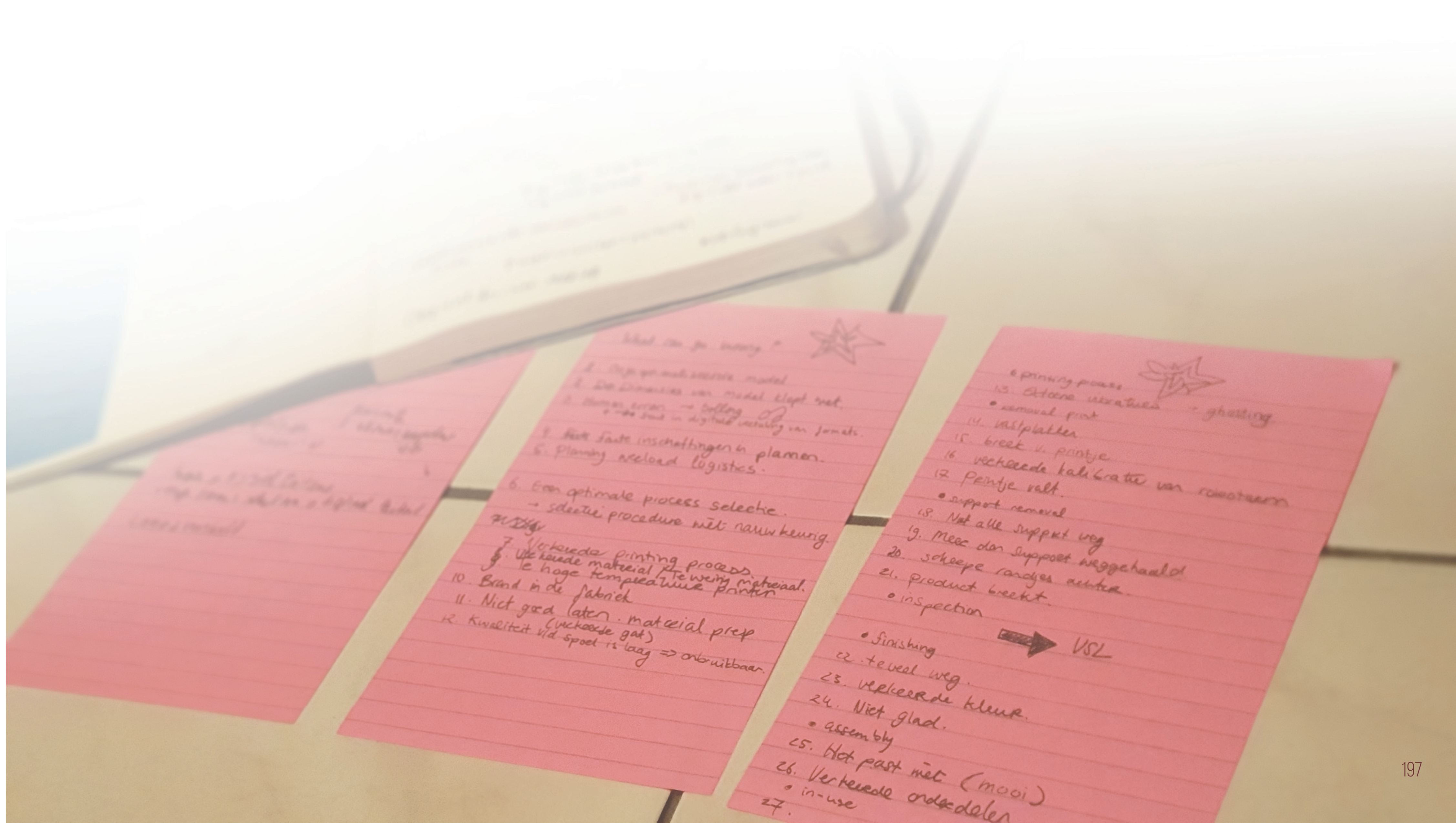




APPENDIX P

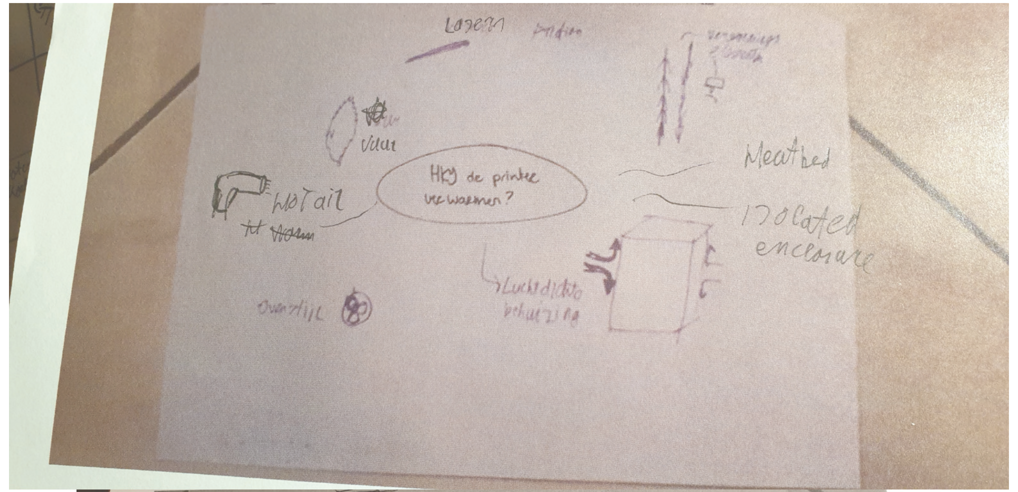
First possible solutions

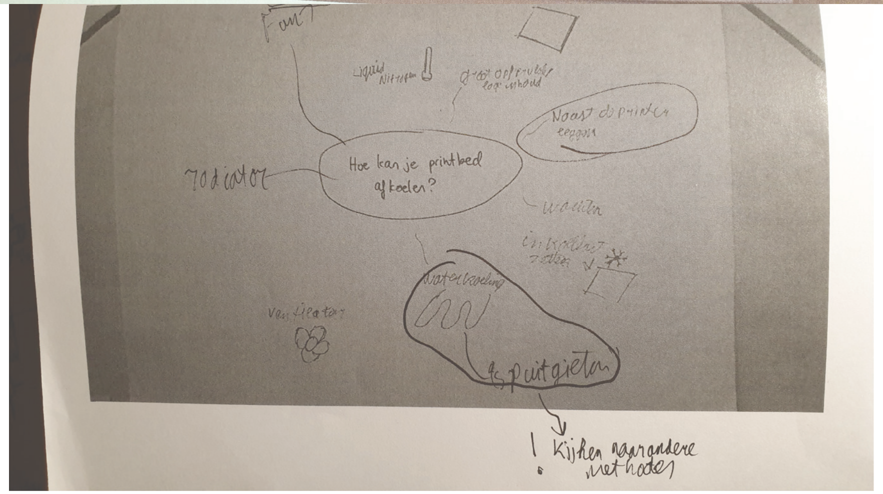
- Printer runs out of material
  - Ability to connect multiple spools
  - Multiple feeders per extruder
  - Printing with fibers instead of spools
- Layer shifting
  - Sensors that recognize this phenomenon
    - Sensor in the stepper motors, that recognizes where the extruder should be
    - Camera's that detect it
  - Solve, if possible, otherwise stop print, check if damage can be fixed, remove part of the print and continue printing
  - Data of error saved, so it can be prevented
- Wrong tolerances
  - Real-time monitoring of the process, in case of wrong tolerances, automatically adjust for next prints
- Material shrinks during print
  - Surrounding temperature adjusted and maintained exactly depending on material
- Unplanned maintenance is needed
  - Recognize errors and wear in moving parts
  - Performance database (big data)
- Printer is not calibrated well
  - Camera's that recognize this happening
- Support material is not removed well
  - Scan what must be removed further
  - Back to support removal station
- Robot arm cannot remove print
  - Interchangeable hands, multiple options fit for any type of product
  - Removable printbed
  - Flexible printbed (remove print by bending printbed)
- The printed object falls
  - Pick up and scan again
  - In case of a fracture reprint the broken component on the object
- Nozzle jam
  - Recognize the jam
  - Use robotic hand to stick a needle in the nozzle
  - Place a new nozzle
- Oven has to change temperature, a queue starts
  - Send message to printers, storage location for waiting prints
- Transport from and towards scanner is time consuming
  - Integrate scanner in robotic arm
  - Integrate scanner inside printer
  - Multiple scanning stations
- Print must be held during post processing steps (support removal, smoothening, painting etc.)
  - Print a gripping piece along with product
  - Held by airflow (Festo Bernoulli Gripper OGGB)
  - Suction cups

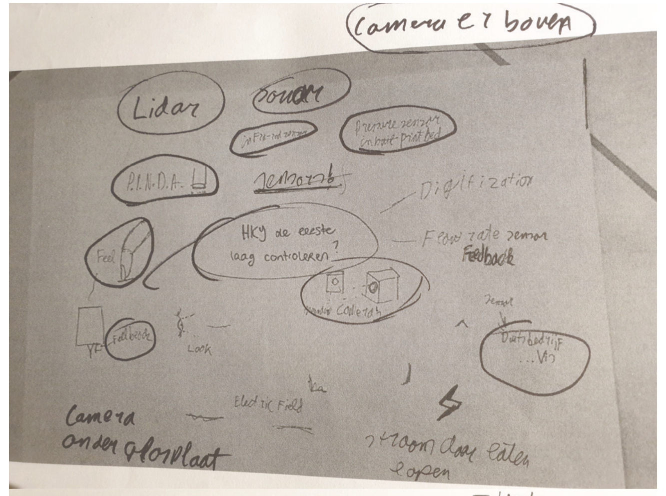


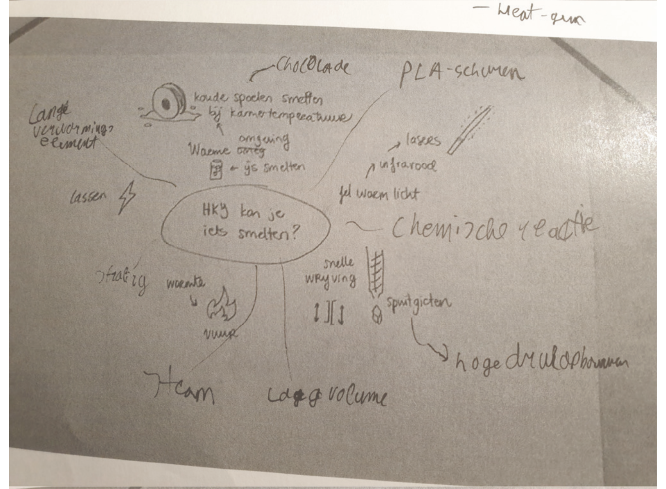
APPENDIX Q

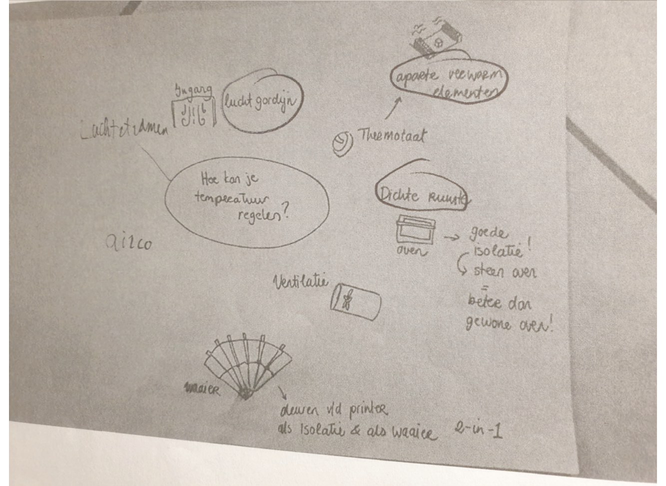
How-to's

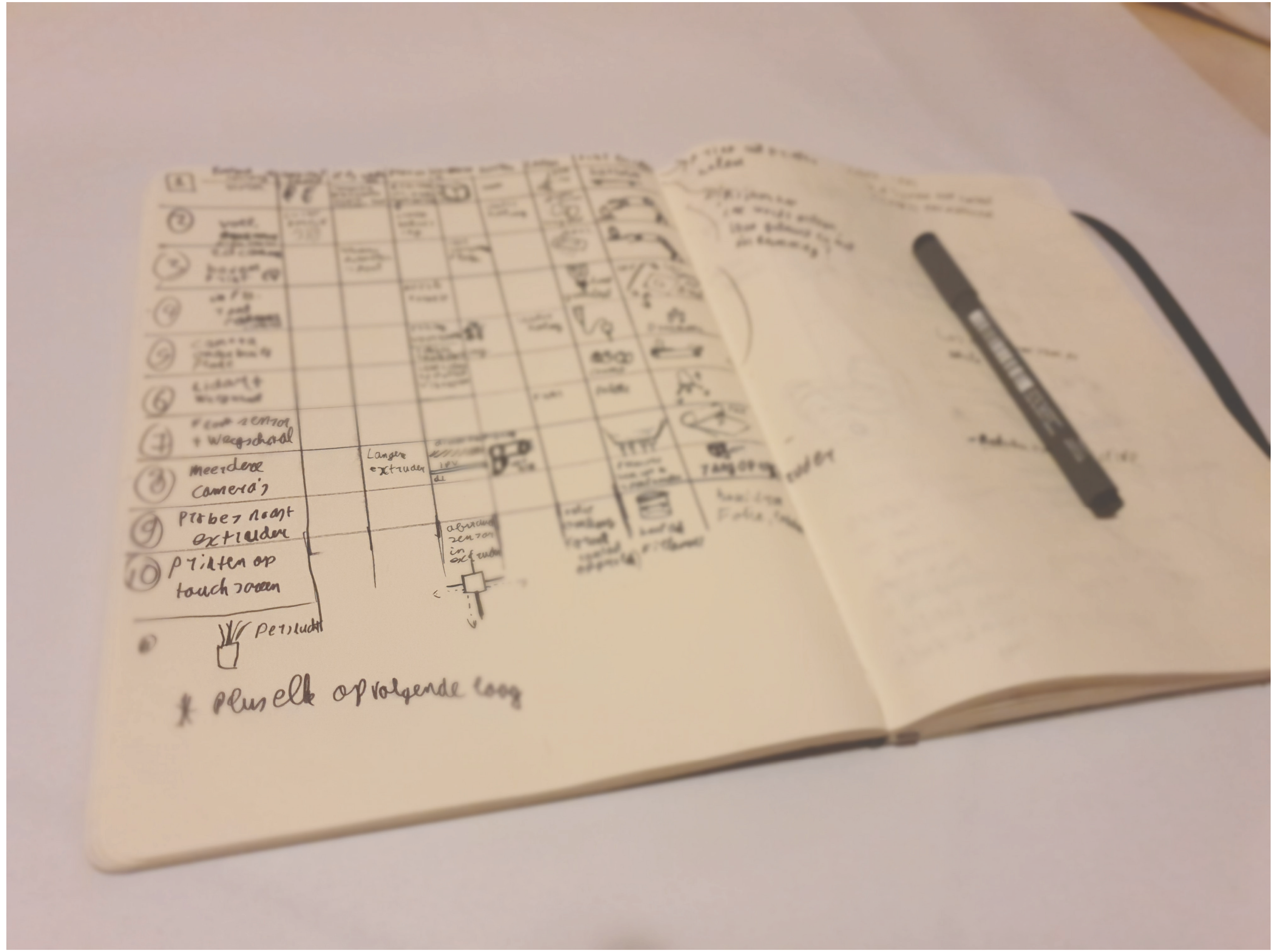




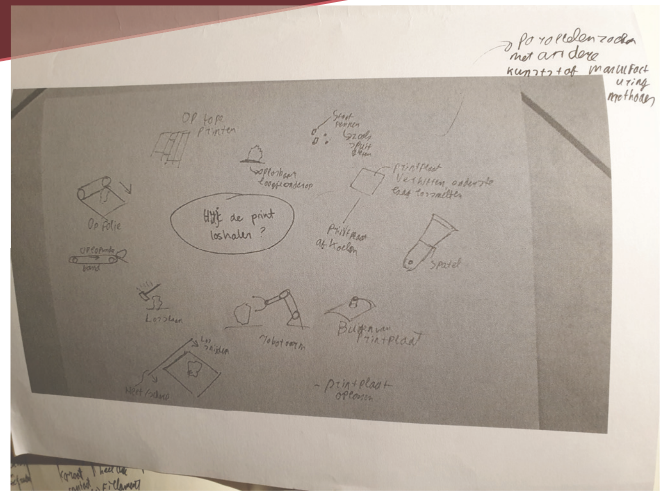


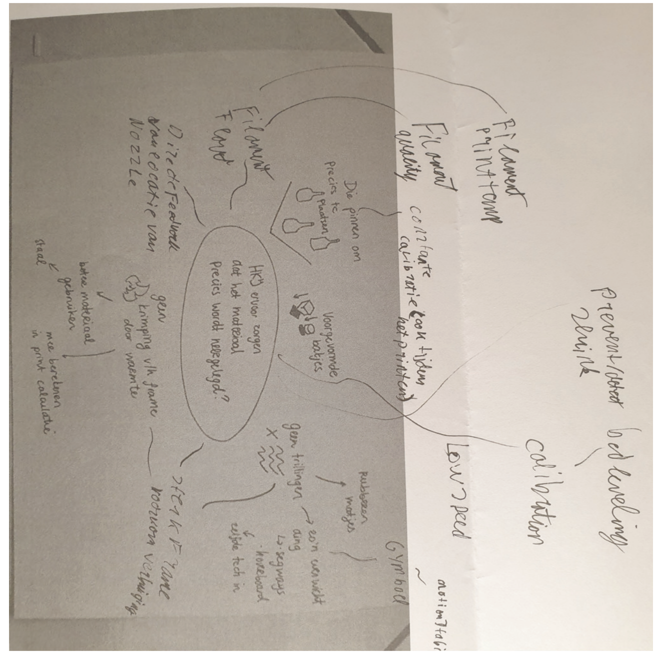


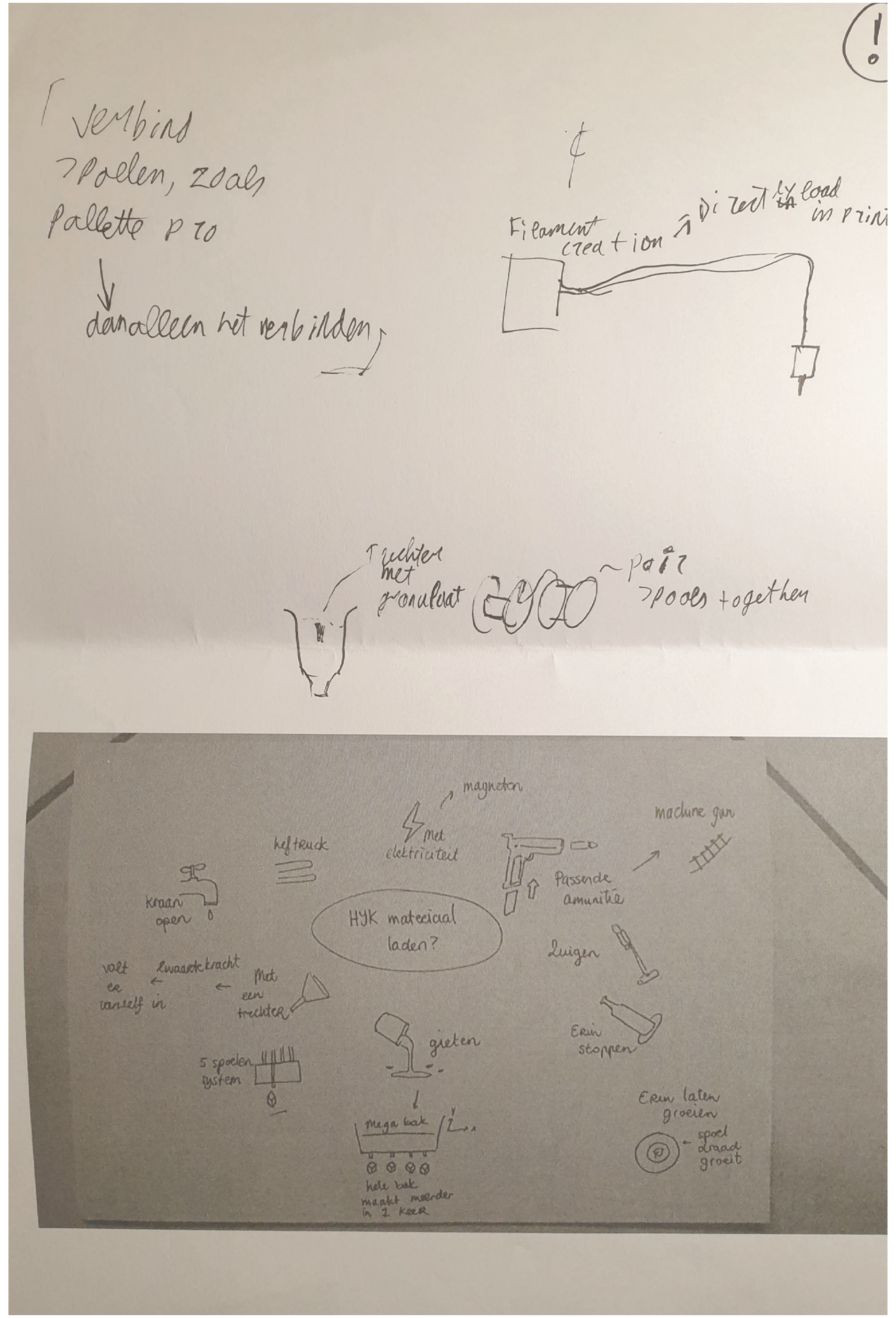


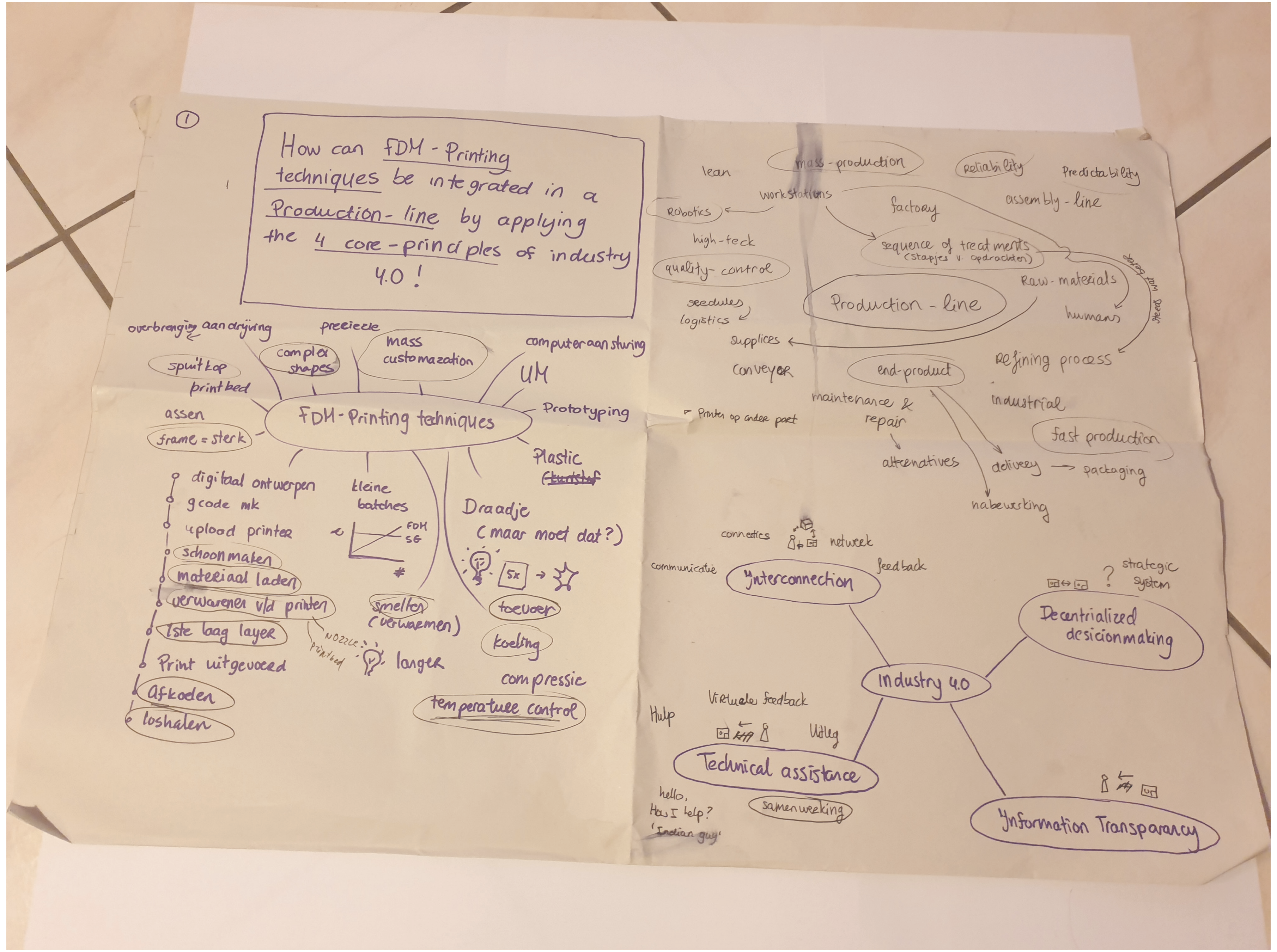


APPENDIX Q



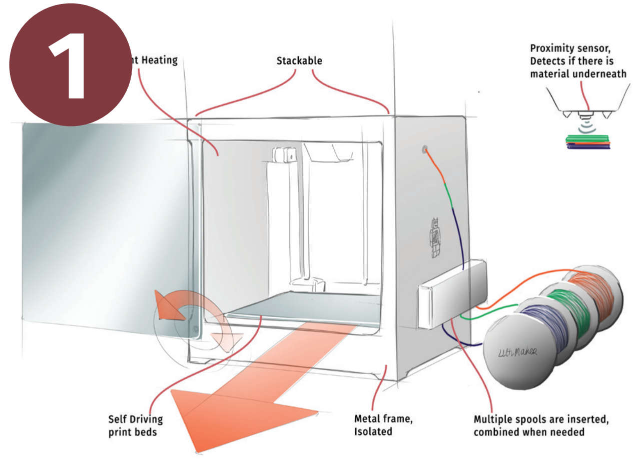


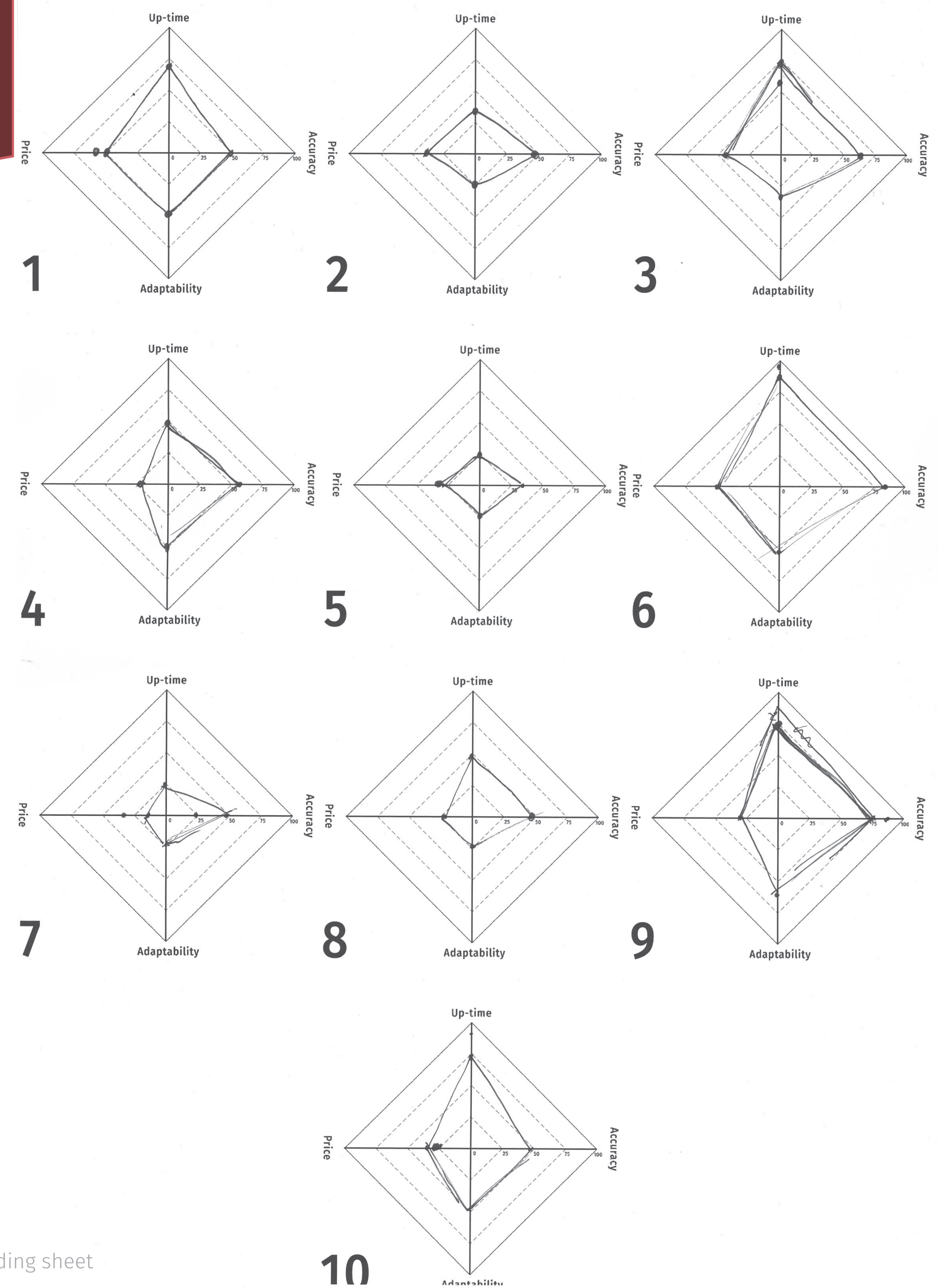


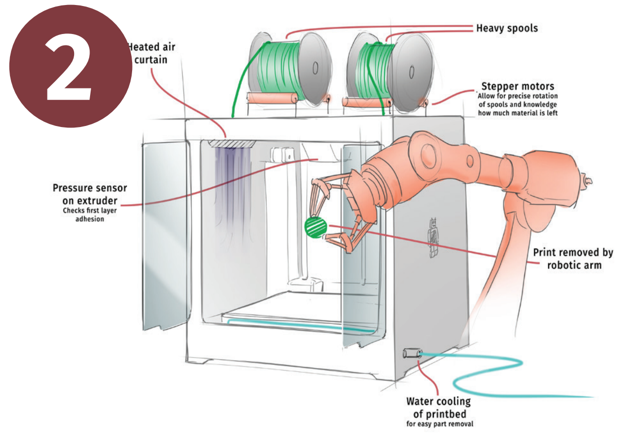

How can FDM - Printing techniques be integrated in a Production-line by applying the 4 core-principles of industry 4.0 !
Production - line
Industry 4.0
Interconnection
Technical assistance
Information Transparancy
Decentrialized desicionmaking

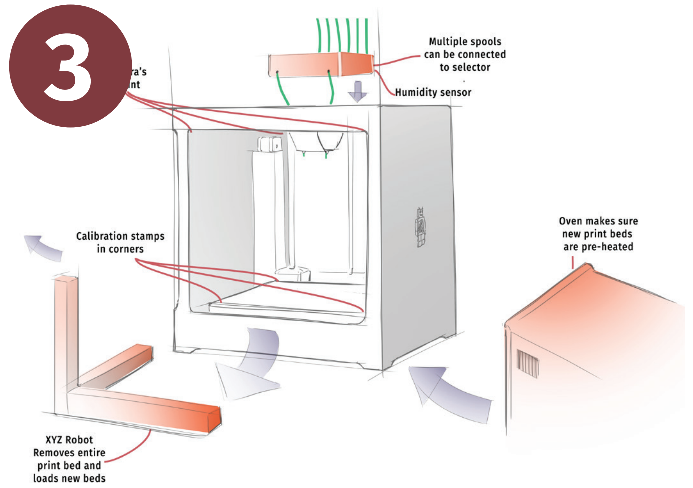
APPENDIX R

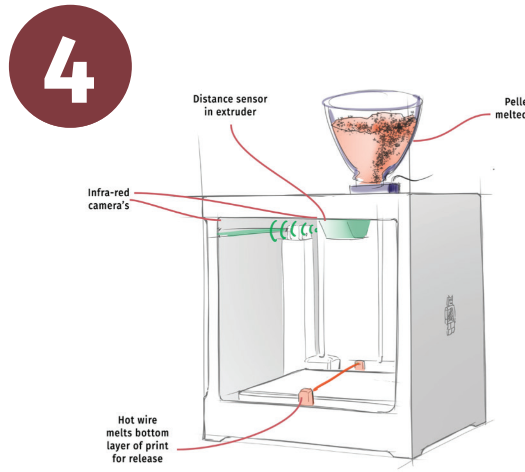
Grading Sheet

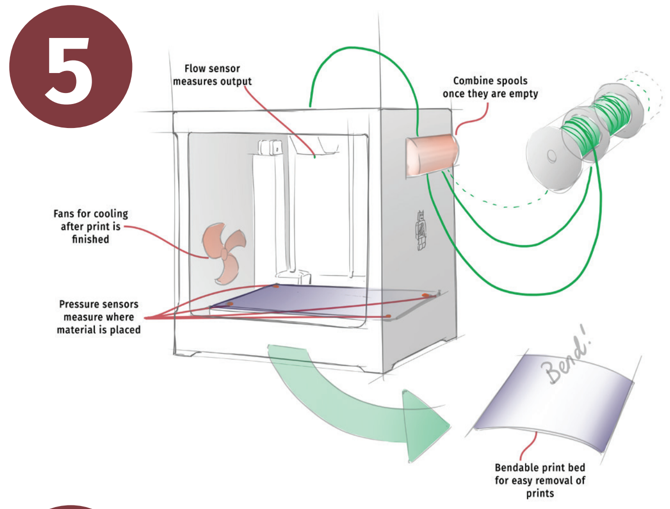


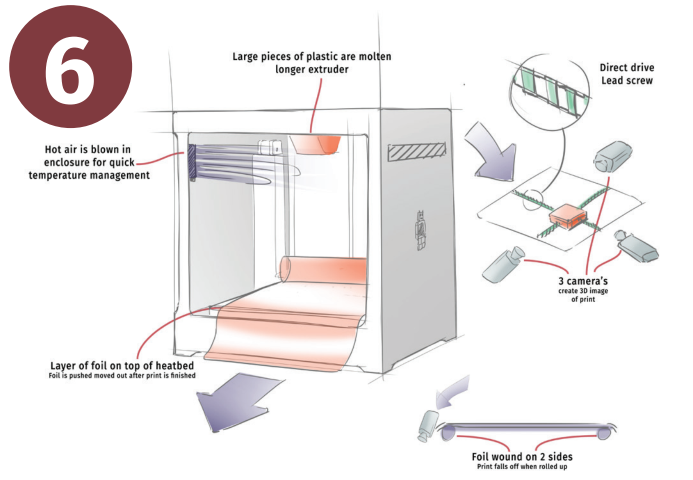


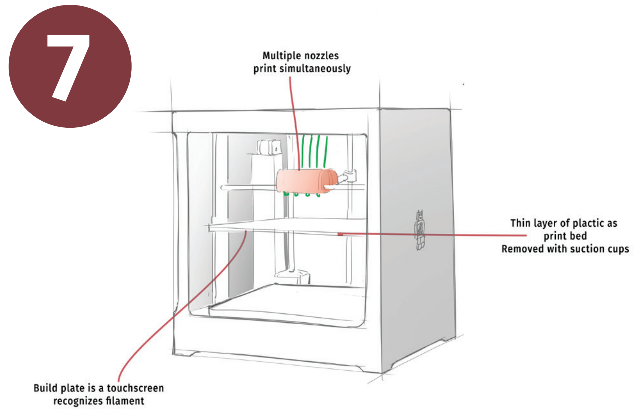


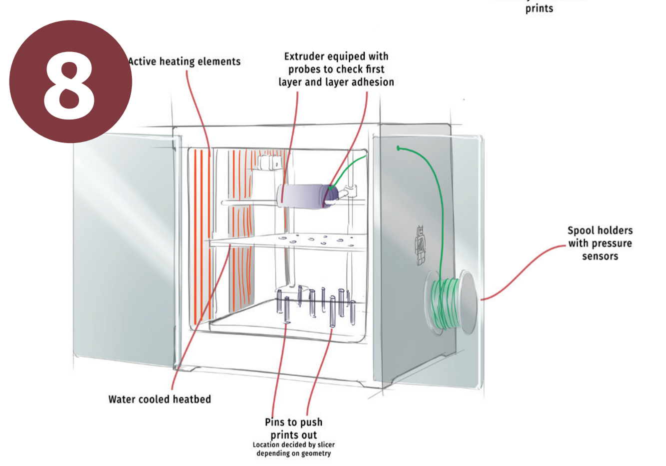


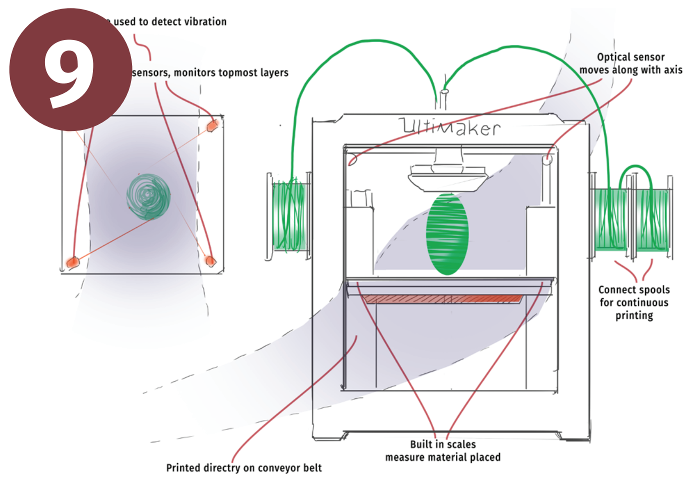


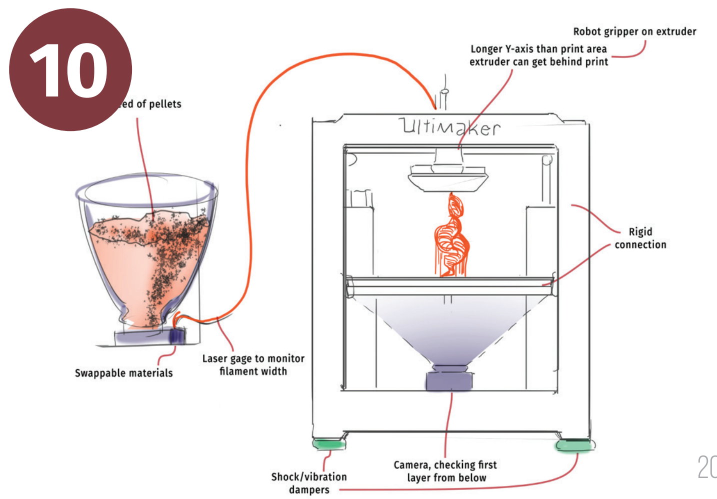








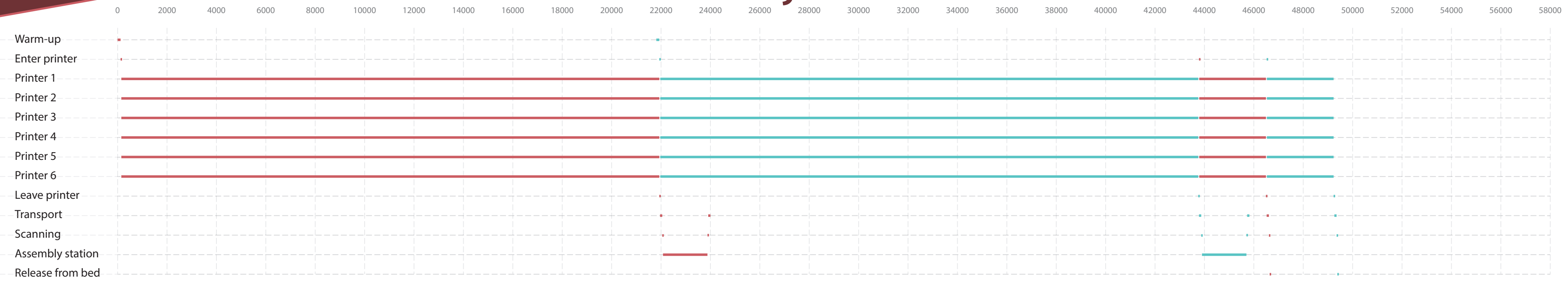




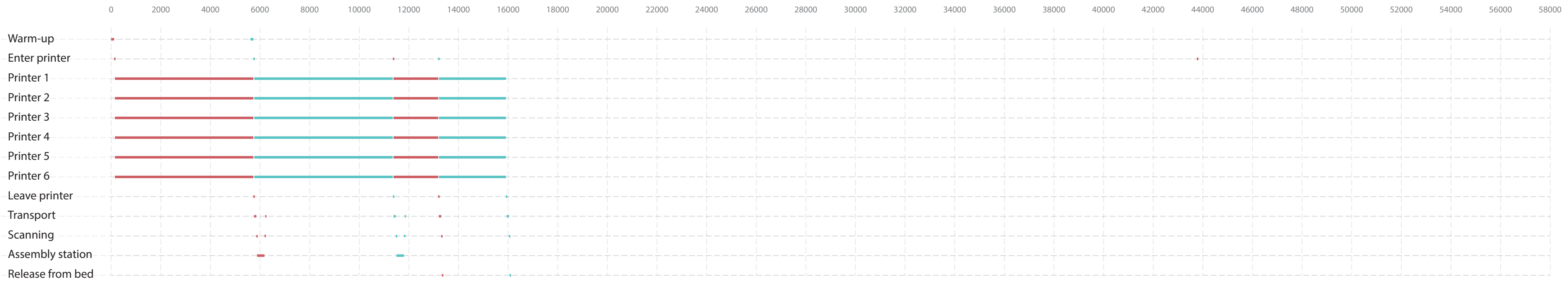
APPENDIX S

Concept 1

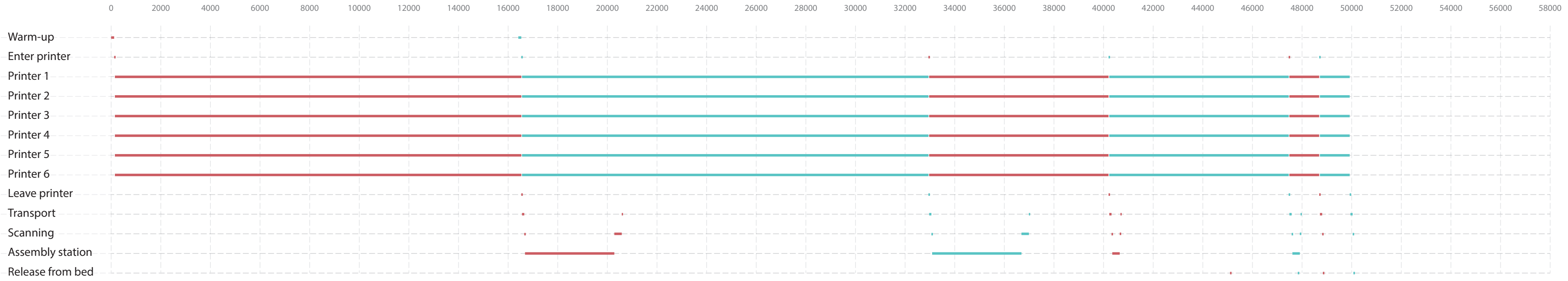
Hand Dynamo



EXO-L

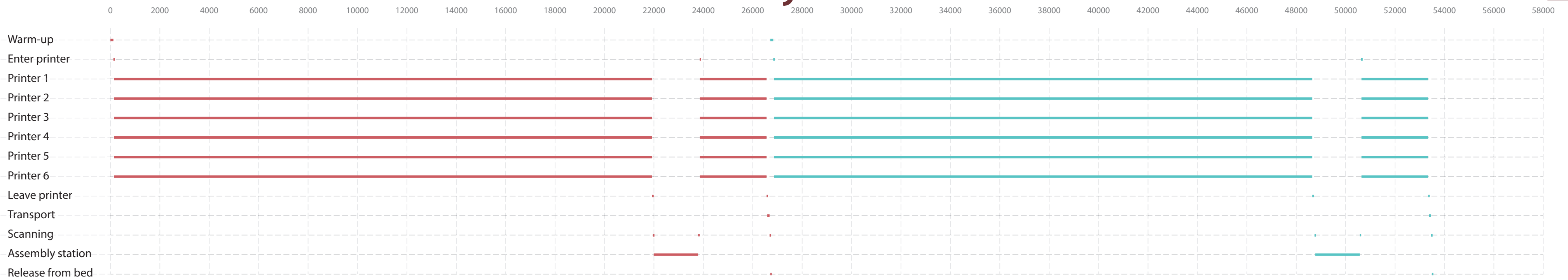


I-SEE

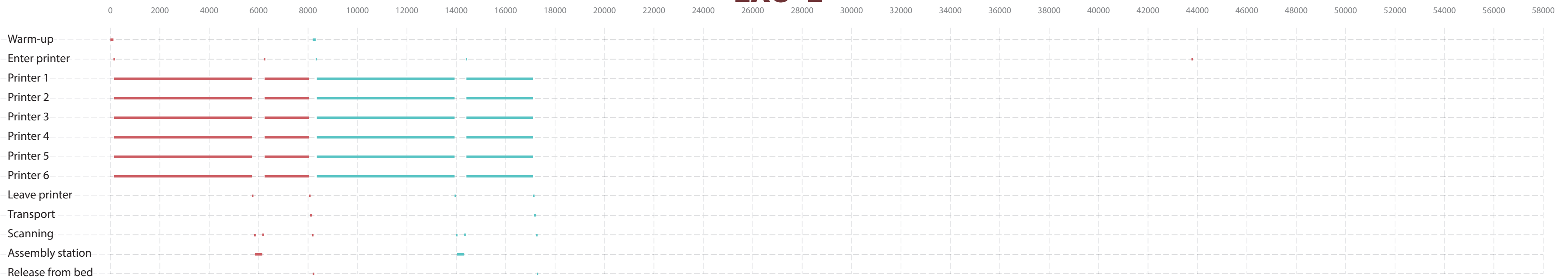


Concept 2

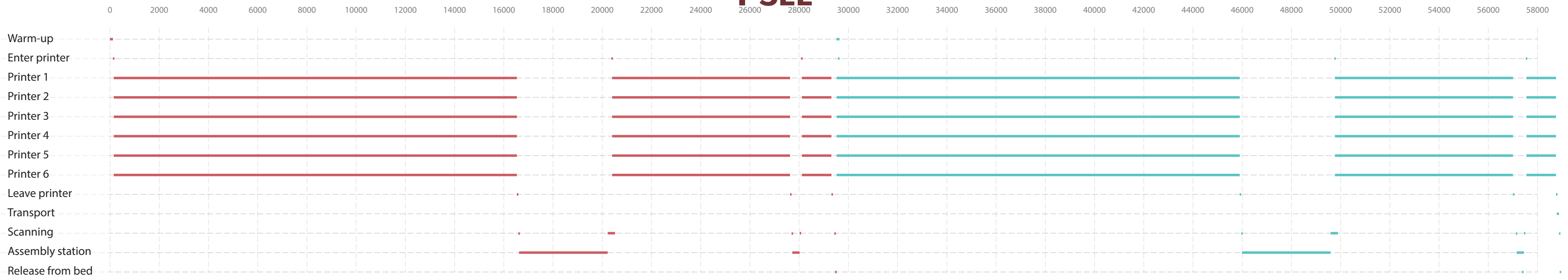
Hand Dynamo



EXO-L

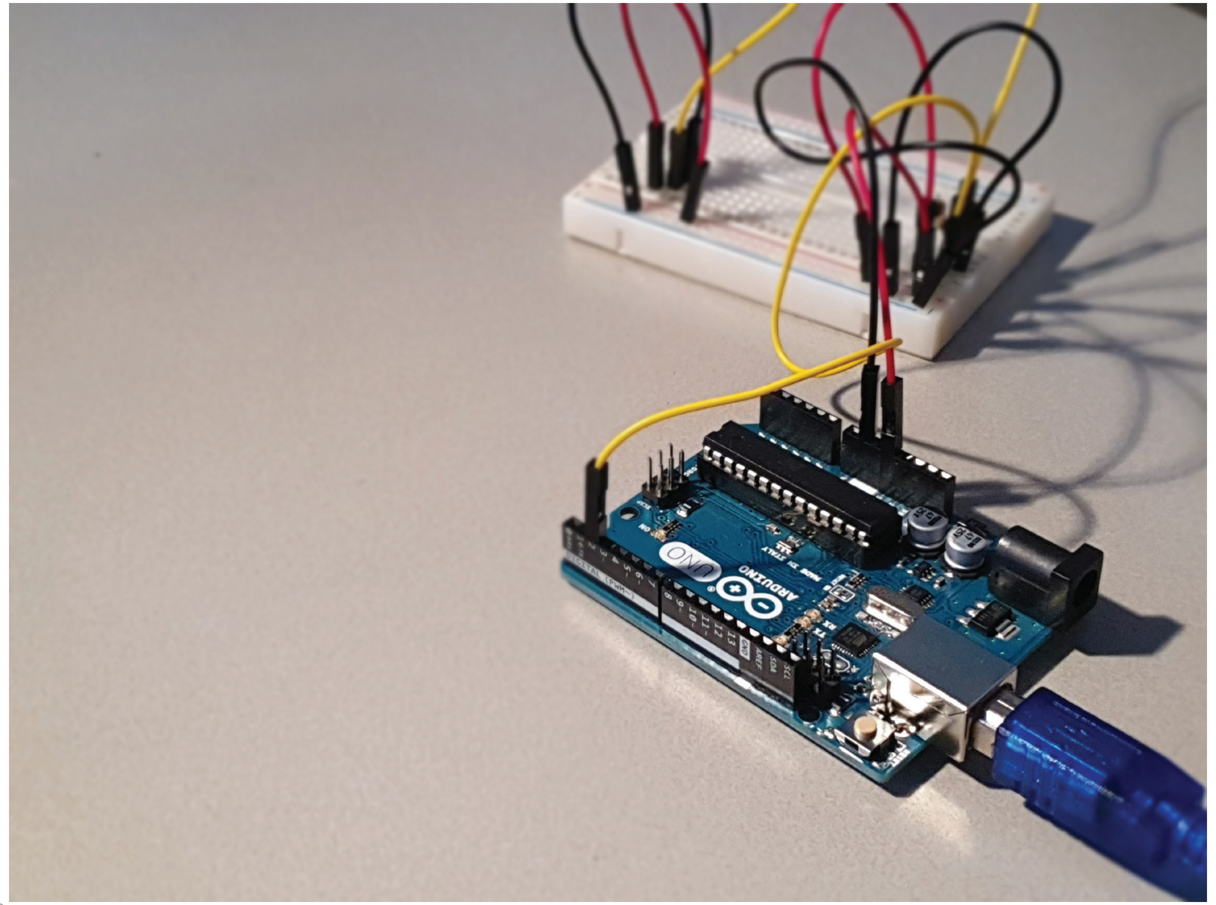


I-SEE



APPENDIX T

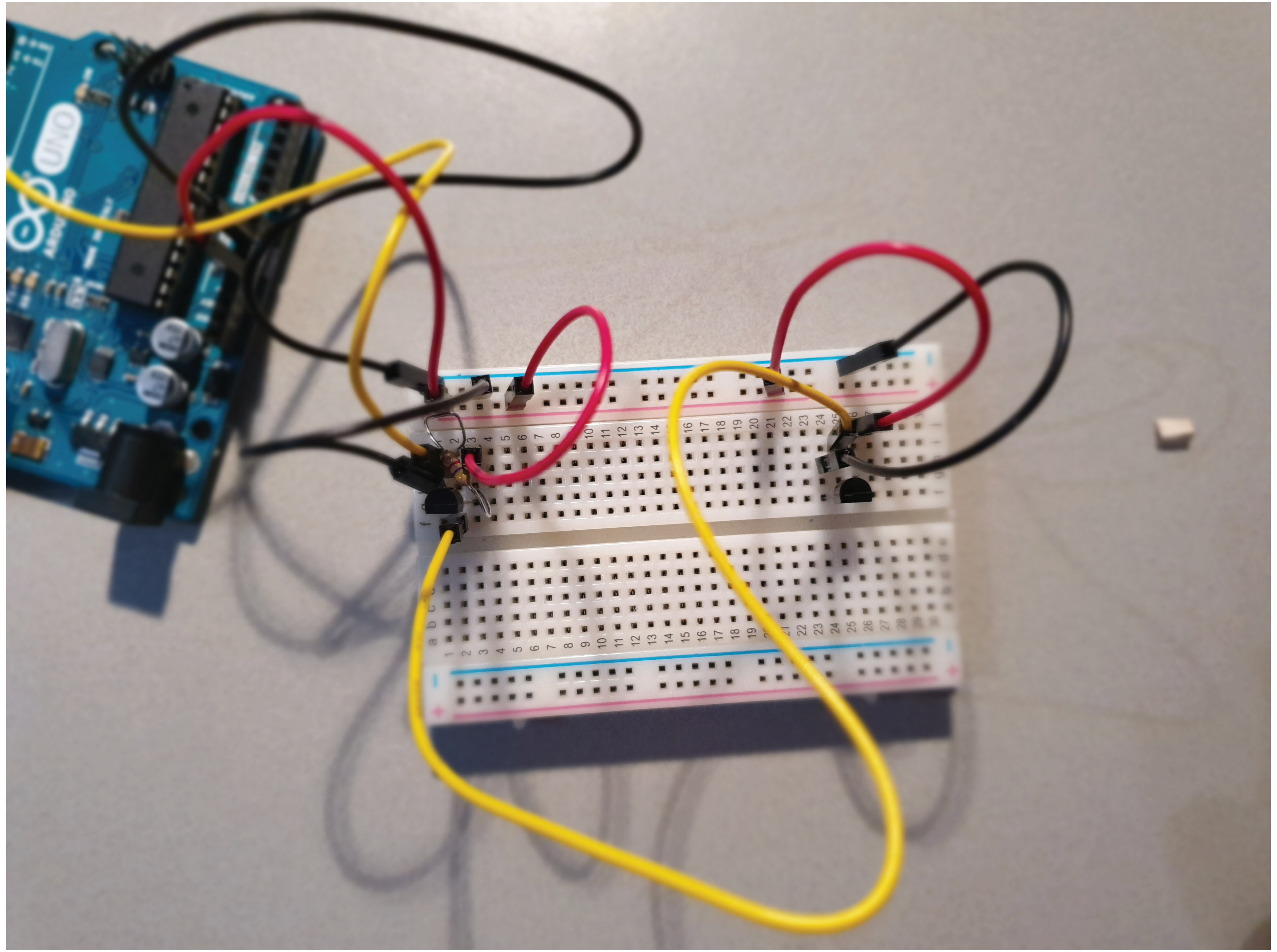
Arduino temperature



Verify

Temptester §

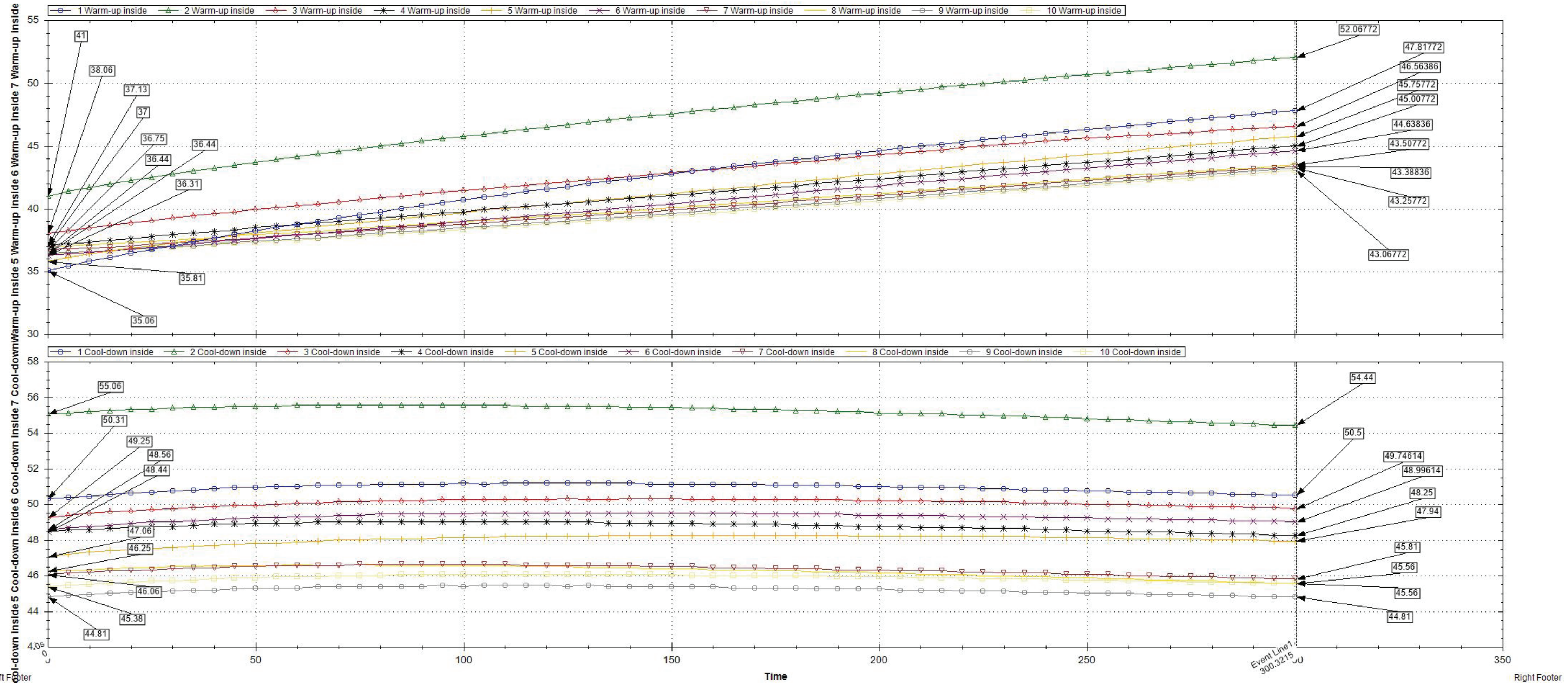
```
#include <OneWire.h>
int counter = 0;
OneWire  ds(2);  // on pin 2
void setup(void) {
  Serial.begin(9600);
}
void loop(void) {
  int (x);
  int y;
  byte i;
  byte present = 0;
  byte type_s;
  byte data[12];
  byte addr[8];
  float celsius;
    if ( !ds.search(addr)) {
    Serial.println("");
    ds.reset_search();
counter++;
counter++;
counter++;
counter++;
counter++;
    delay(3500);
      Serial.print(counter);
    return;
  }
   ds.reset();
  ds.select(addr);
  ds.write(0x44, 1);
   delay(750);
   present = ds.reset();
  ds.select(addr);
  ds.write(0xBE);
  for ( i = 0; i < 9; i++) {
    data[i] = ds.read();
  }
  int16_t raw = (data[1] << 8) | data[0];
  if (type_s) {
    raw = raw << 3;
    if (data[7] == 0x10) {
      raw = (raw & 0xFFF0) + 12 - data[6];
    }
  } else {
    byte cfg = (data[4] & 0x60);
     if (cfg == 0x00) raw = raw & ~7;
    else if (cfg == 0x20) raw = raw & ~3;
    else if (cfg == 0x40) raw = raw & ~1;
  }
  celsius = (float)raw / 16.0;
    Serial.print(", ");
  Serial.print(celsius);
}
```



APPENDIX U

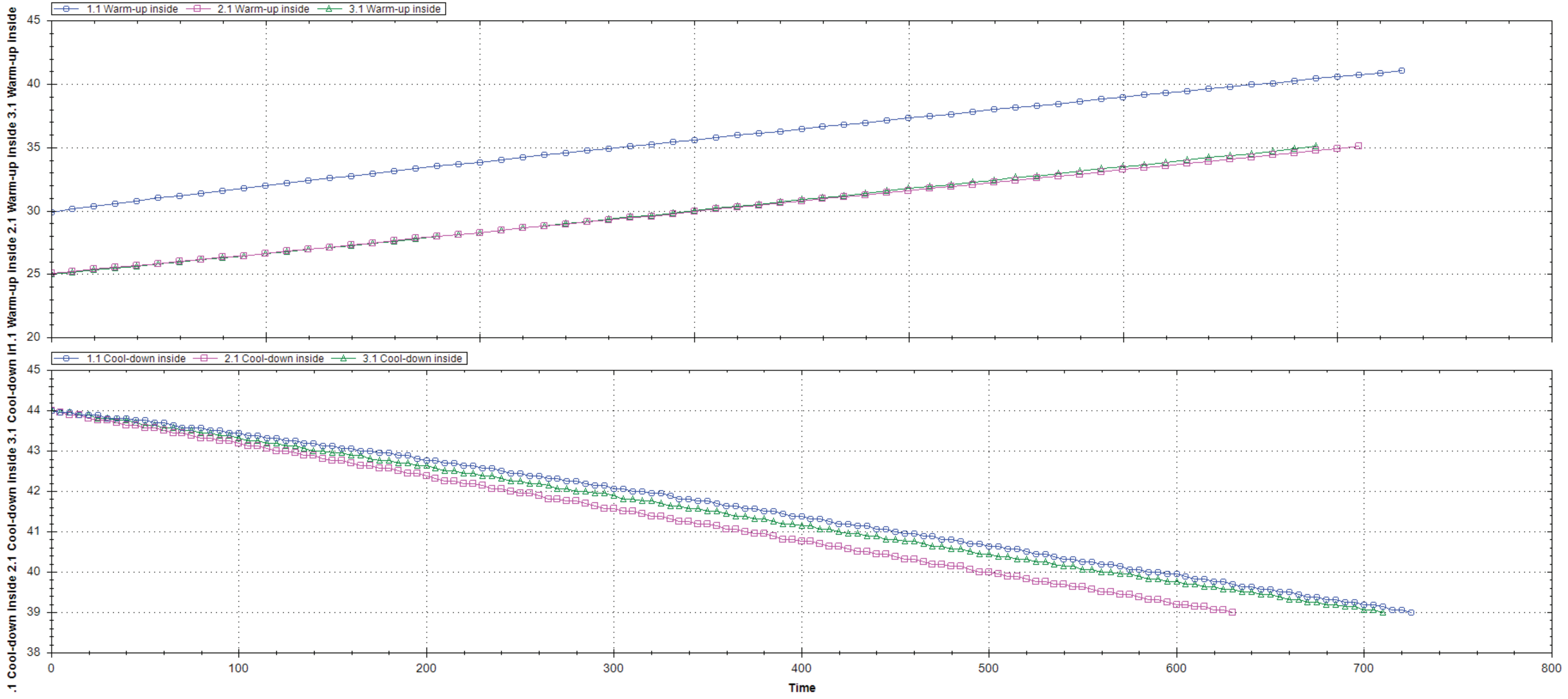
Results heat curtains

First tests, 10 materials



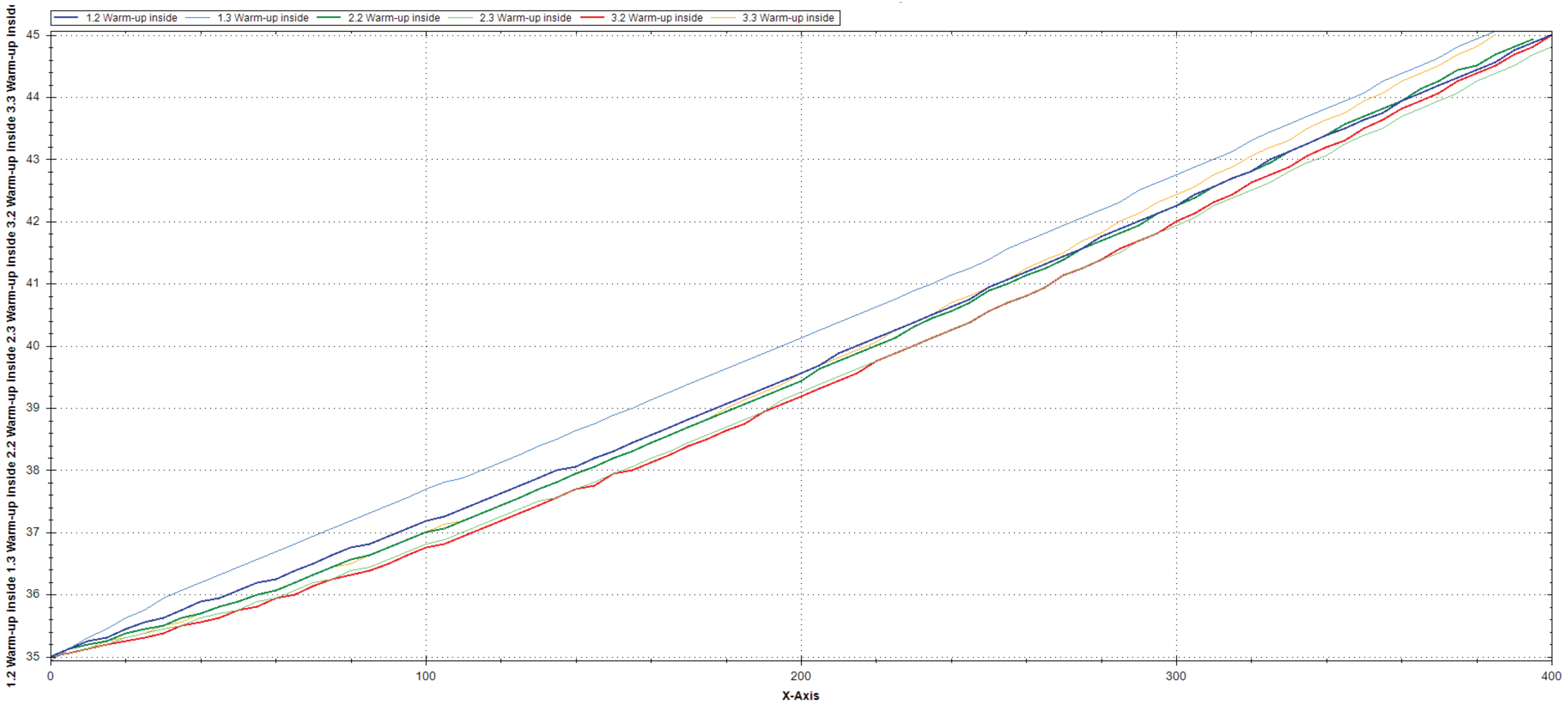
Second tests, 3 materials first round

First warm up & cooldown

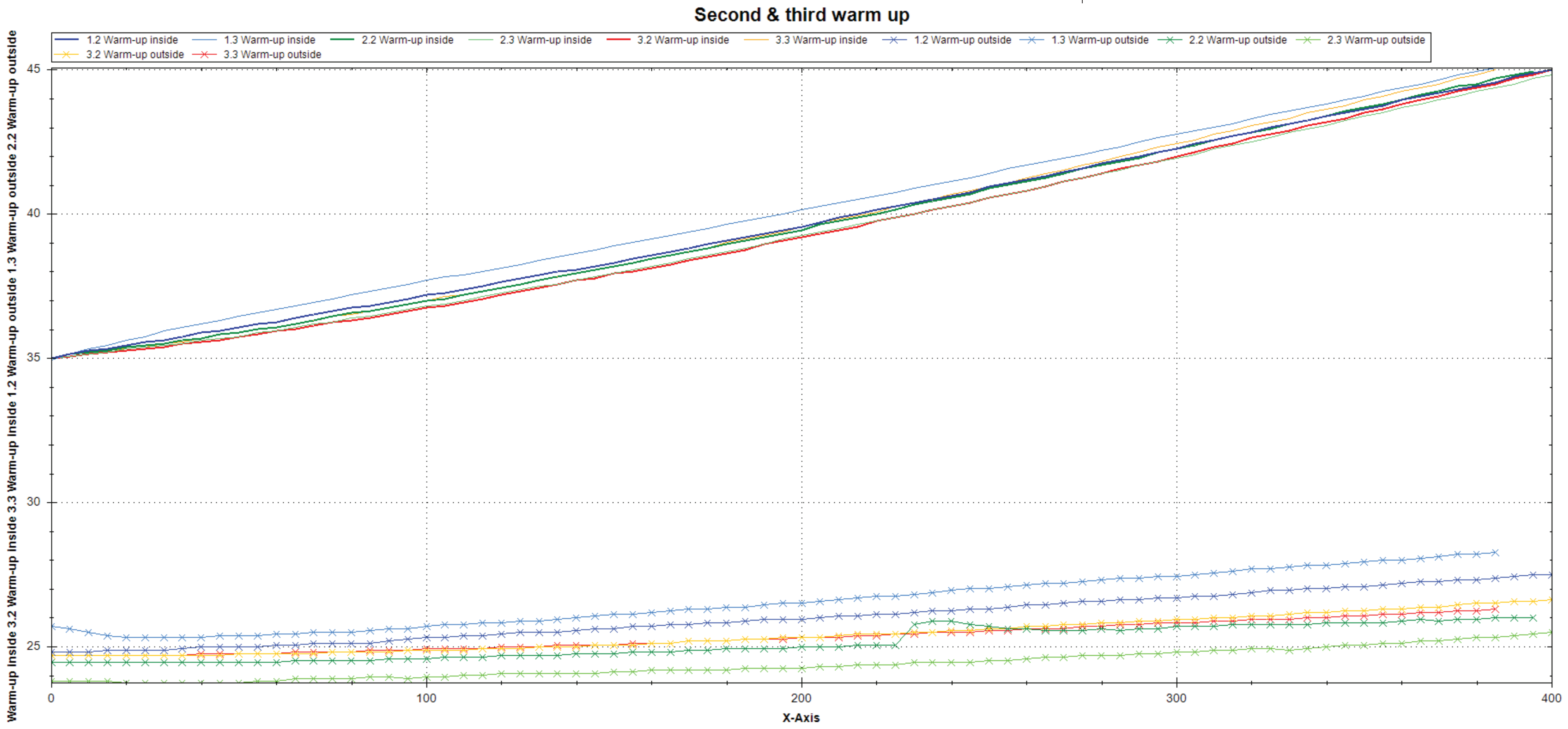


APPENDIX U

Second tests, 3 materials second and third round inside warm-up

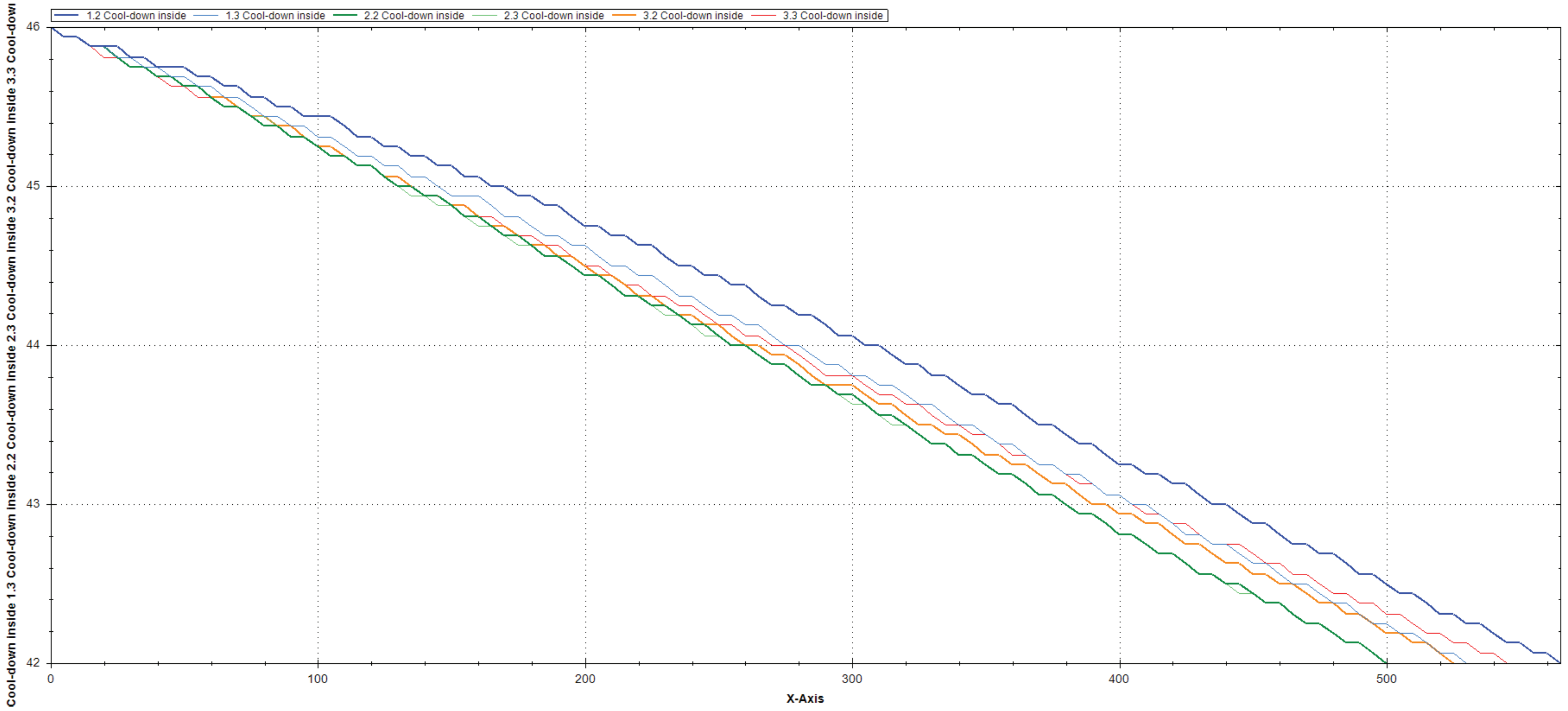


Second tests, 3 materials second and third round inside and outside warm-up

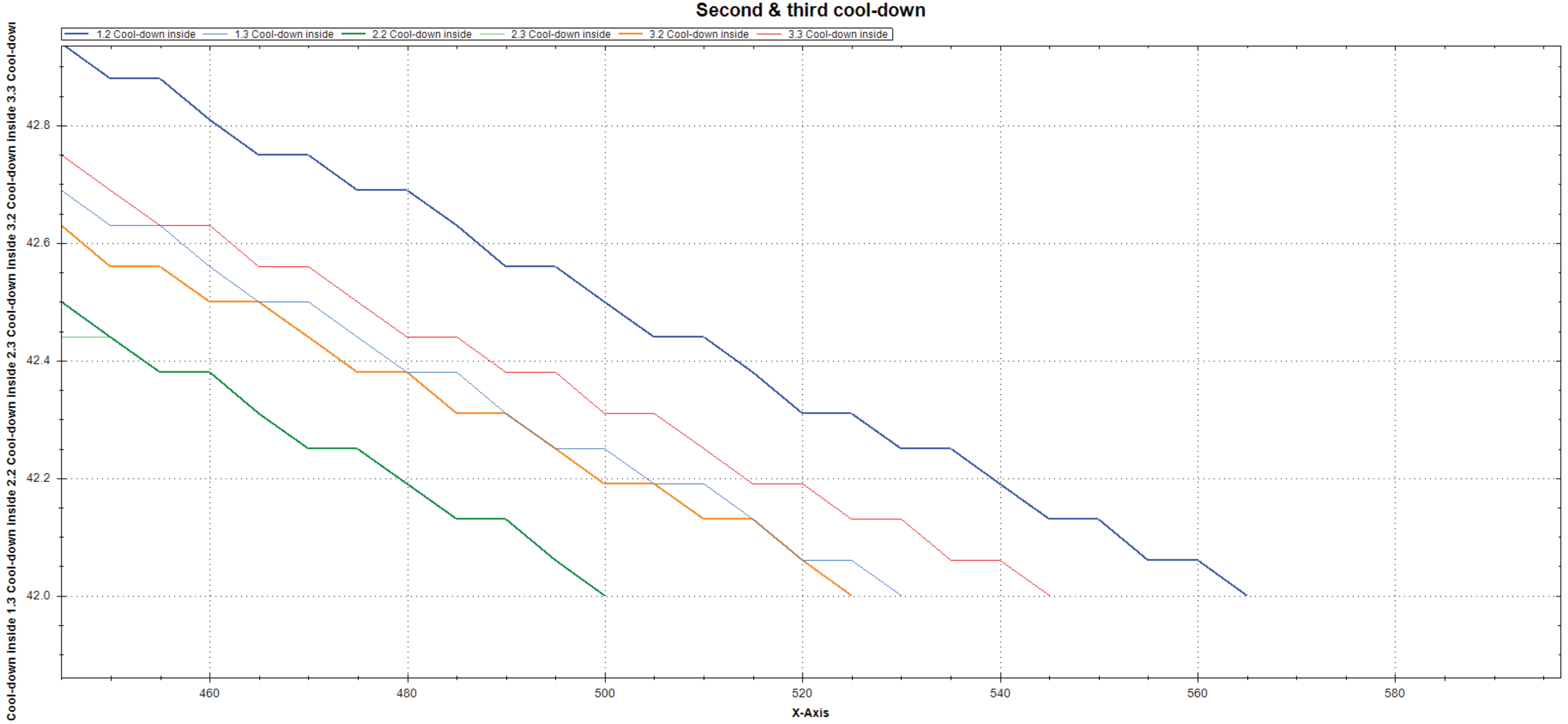


APPENDIX U

Second tests, 3 materials second and third round inside cool-down

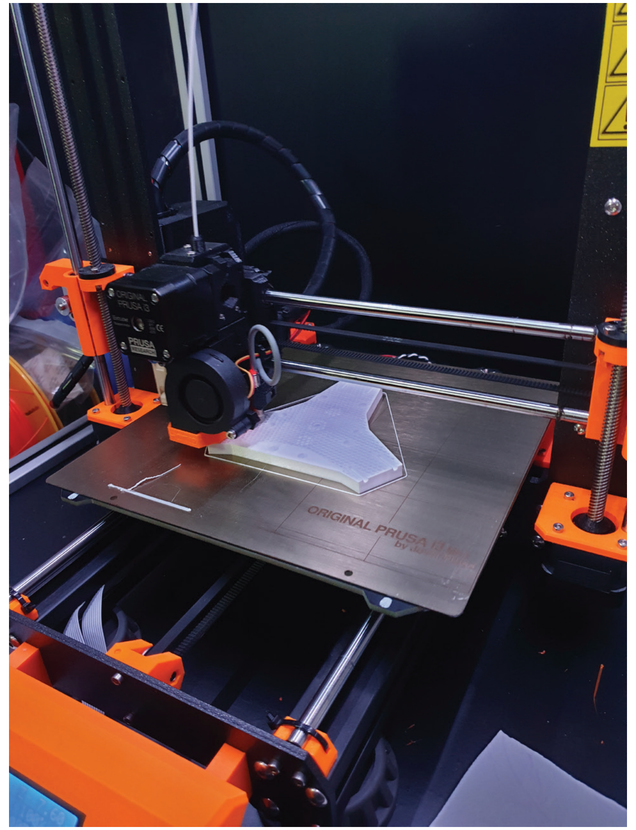


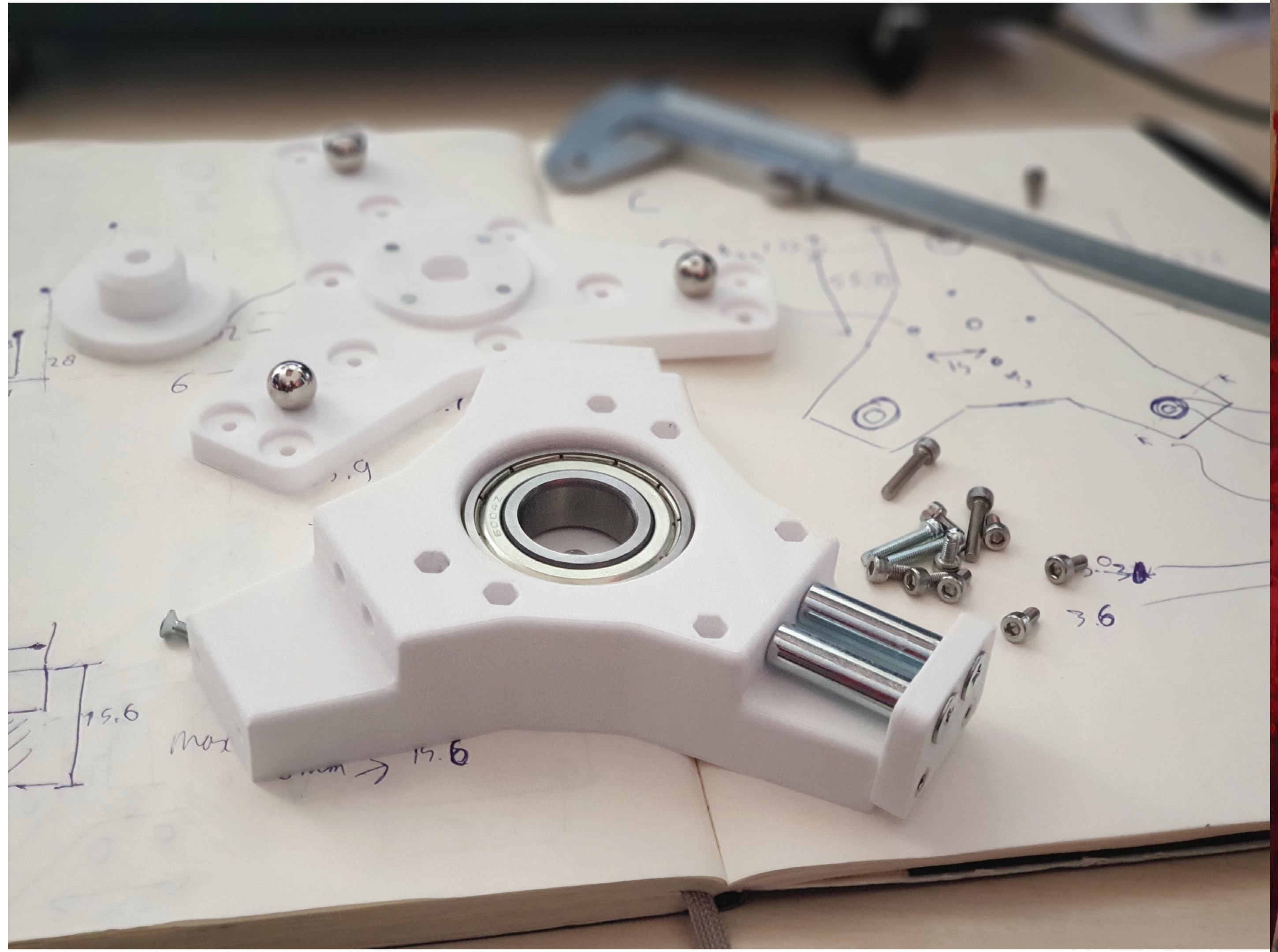
Second tests, 3 materials second and third round inside cool-down (ZOOM)



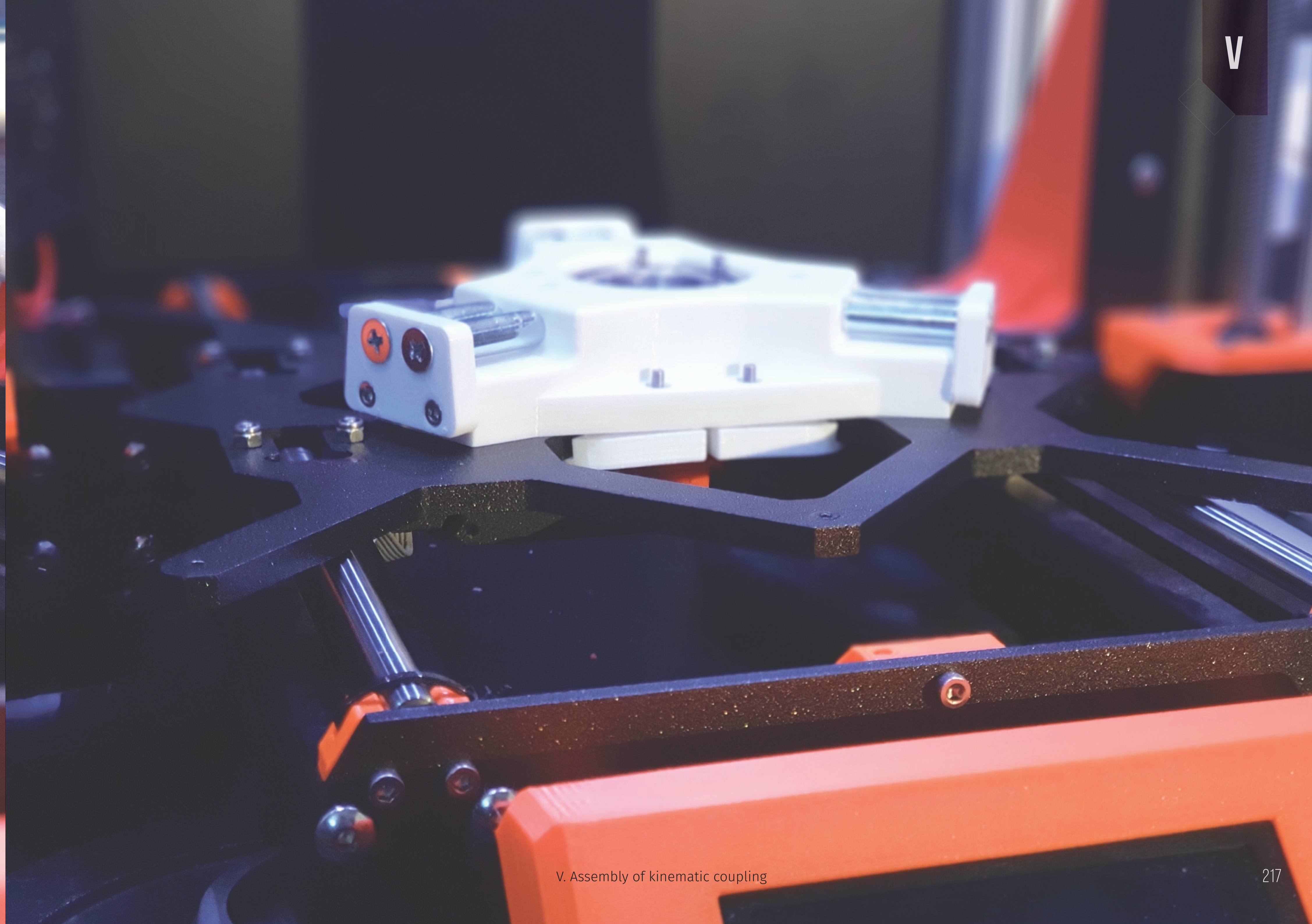
APPENDIX V

Assembly of kinematic coupling





APPENDIX V



V

APPENDIX W

Kinematic coupling precision measurements

Measurements from the top

#1	0.00	#11	0.01	#21	0.02	#31	0.01	#41	0.00	#51	0.01
#2	0.00	#12	0.02	#22	0.01	#32	0.01	#42	0.00	#52	0.01
#3	0.00	#13	0.01	#23	0.01	#33	0.01	#43	0.00	#53	0.01
#4	0.00	#14	0.01	#24	0.02	#34	0.01	#44	0.01	#54	0.01
#5	0.01	#15	0.02	#25	0.01	#35	0.01	#45	0.01	#55	0.01
#6	0.01	#16	0.02	#26	0.02	#36	0.01	#46	0.01	#56	0.01
#7	0.01	#17	0.02	#27	0.02	#37	0.01	#47	0.01	#57	0.01
#8	0.02	#18	0.02	#28	0.01	#38	0.01	#48	0.01	#58	0.01
#9	0.01	#19	0.02	#29	0.02	#39	0.01	#49	0.01	#59	0.02
#10	0.01	#20	0.02	#30	0.01	#40	0.00	#50	0.01	#60	0.02

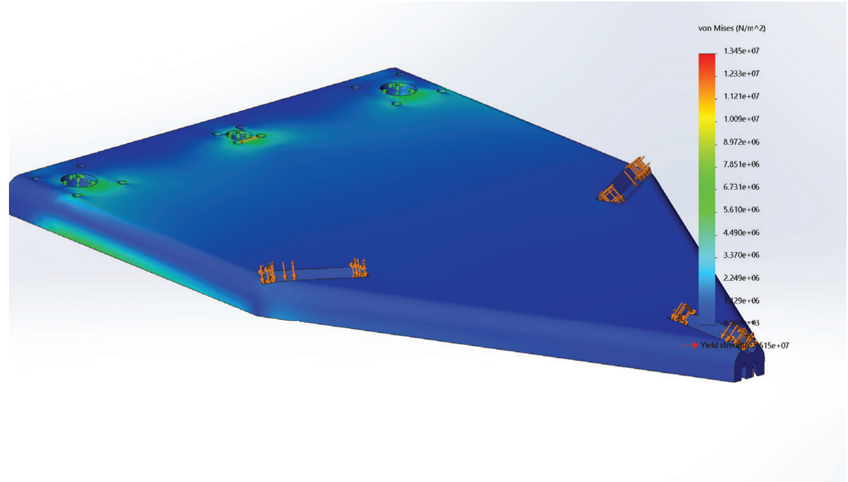
Measurements from the side

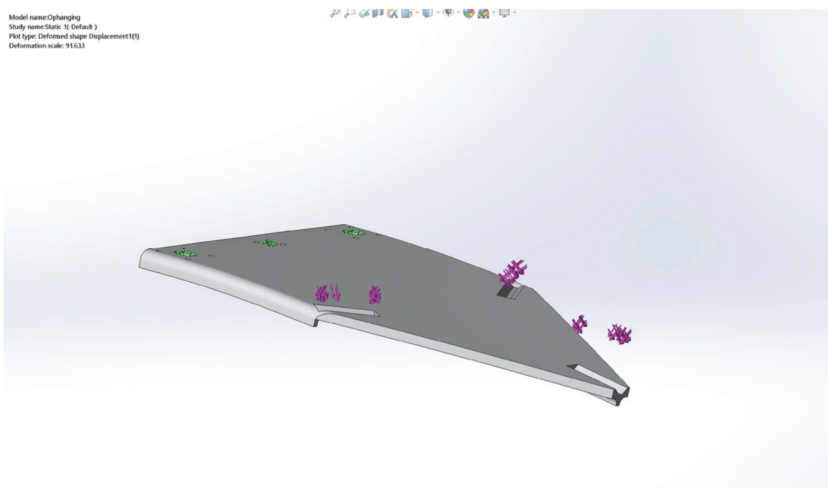
#1	2.87	#11	2.87	#21	2.87	#31	2.87	#41	2.87	#51	2.87
#2	2.87	#12	2.87	#22	2.87	#32	2.87	#42	2.87	#52	2.87
#3	2.87	#13	2.87	#23	2.87	#33	2.87	#43	2.87	#53	2.87
#4	2.87	#14	2.87	#24	2.87	#34	2.87	#44	2.87	#54	2.87
#5	2.87	#15	2.87	#25	2.87	#35	2.87	#45	2.87	#55	2.87
#6	2.87	#16	2.87	#26	2.87	#36	2.87	#46	2.87	#56	2.87
#7	2.87	#17	2.87	#27	2.87	#37	2.87	#47	2.87	#57	2.87
#8	2.87	#18	2.87	#28	2.87	#38	2.87	#48	2.87	#58	2.87
#9	2.87	#19	2.87	#29	2.87	#39	2.87	#49	2.87	#59	2.87
#10	2.87	#20	2.87	#30	2.87	#40	2.87	#50	2.87	#60	2.87

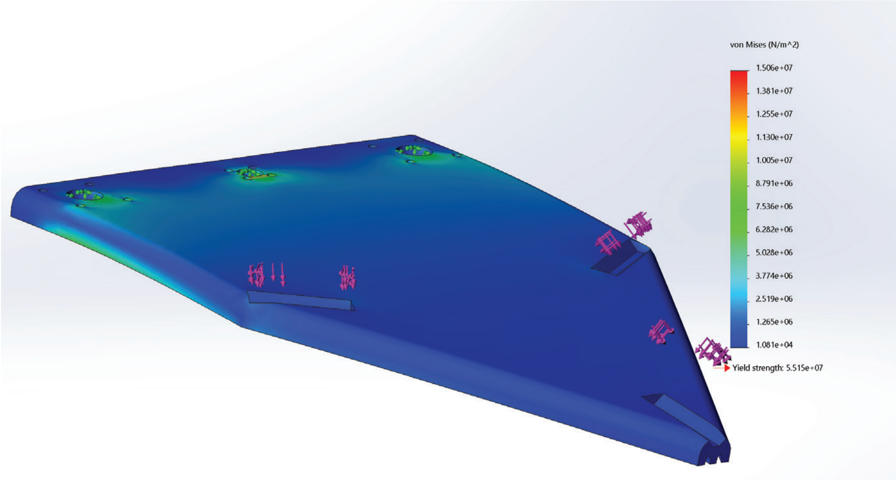
W. Kinematic coupling precision measurements

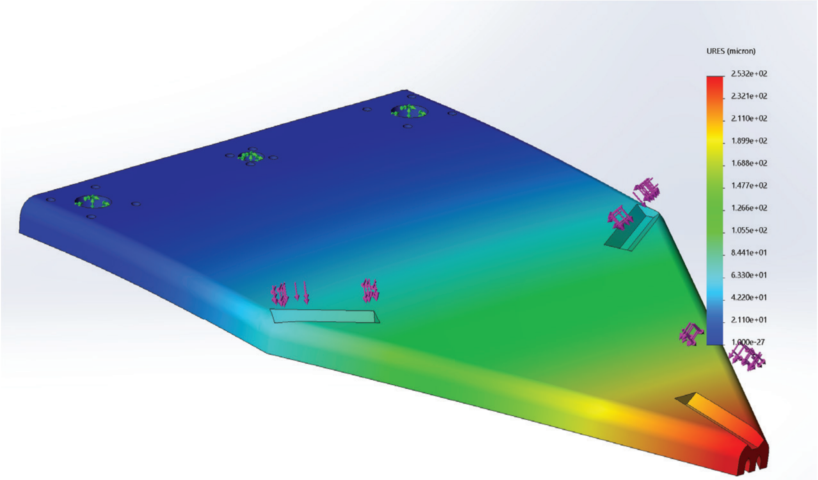
APPENDIX X

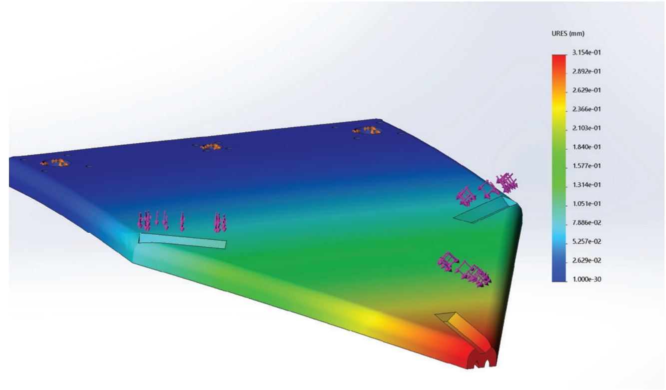
Simulation of Z-axis plate

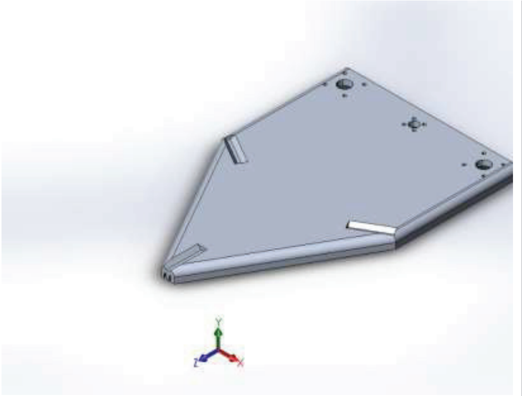












Simulation of Ophangingtest

Date: Monday, 13 May, 2019
Designer: Solidworks
Study name: Static 1
Analysis type: Static

Table of Contents

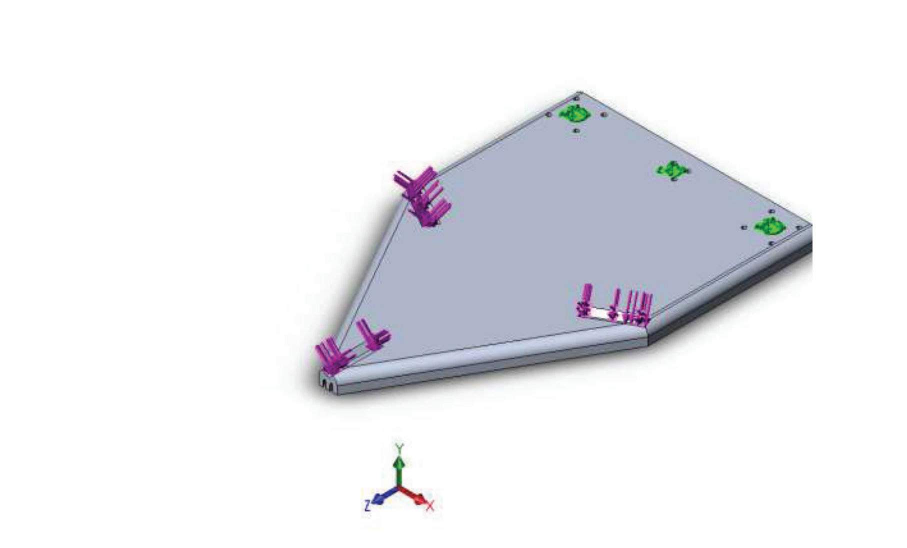
Description 1
Assumptions 2
Model Information 2
Study Properties 3
Units 3
Material Properties 4
Loads and Fixtures 4
Connector Definitions 5
Contact Information 5
Mesh information 5
Sensor Details 5
Resultant Forces 5
Beams 6
Study Results 7
Conclusion 10

Description

No Data

Assumptions

Model Information



Model name: Ophangingtest
Current Configuration: Default

Solid Bodies			
Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
Cut-Extrude2 	Solid Body	Mass:0.767388 kg Volume:0.000284218 m^3 Density:2700 kg/m^3 Weight:7.5204 N	C:\Users\dc-lo\Documents\Ophangingtest.SLDPRT May 13 00:50:58 2019

APPENDIX Z

Title of appendix