Clickfinger

This profile guides you through the print preparation of clickfinger components to enable the correct mechanical properties.

CAUTION: Orient the clickfingers so deflections are parallel to the XY plane, otherwise they will not function properly.

Flexibility

Making the snap fit more flexible decreases its strength.

Flexibility: Flexible

Ready to Save to File

02h 28min

1.60m / ~ 12g

Intent-Based Material Extrusion 3D Printing:
Moving from process-driven to intent-driven 3D printing

A graduation project by Joost Kuitert

TU Delft

Ultimaker

Joost Kuitert
Address: Kloosterkade 143, 2628HZ, Delft
Email: joost.kuitert@gmail.com
Phone: +31 (0)6 27 35 45 13
Master: Integrated Product Design

Delft University of Technology
Faculty: Industrial Design Engineering
Address: Landbergstraat 15, 2628CE, Delft
Website: http://www.io.tudelft.nl/
Email: io@tudelft.nl
Phone: +31 (0)15 27 89807
Project Chair: Dr. Ir. Z. Ruśak
Project Mentor: Dr. Ir. Zjenja Doubrovski

Ultimaker B.V.
Address: Watermolenweg 2, 4191PN, Geldermalsen
Website: https://ultimaker.com/
Email: info@ultimaker.com
Phone: +31 345 712017
Company mentors: Drs. J. van Kessel & Ir. P. Brier

Master Thesis

Intent-Based Material Extrusion 3D Printing:
Moving from process-driven to intent-driven 3D printing

Graduate student

Joost Kuitert

Master Integrated Product Design
Industrial Design Engineering

Delft University of Technology

Supervisory team

Dr. Ir. Z. Rusak (chair)
Industrial Design Engineering / Cyber-Physical Systems

Dr. Ir. E.L. Doubrovski (mentor)
Industrial Design Engineering / Mechatronic Design

Drs. J. Van Kessel (company mentor)
Software Engineer

Ir. P. Brier (company mentor)
Mechatronic System Architect

Acknowledgements

This graduation project was a tremendous learning experience for me. I would like to thank everyone involved in this project for their contribution in any shape or form. This project would not have been possible without your contributions. Some of you deserve a special mention:

First of all I would like to thank Zoltan Rusak and Zjenja Doubrovski for being a part of my supervisory team. I am glad you sticked with the project even though the subject was under discussion for a long time. Your critical views have had a tremendous positive influence that pushed me towards a better end result. Your criticism was indicative of your care for the end result.

Next, I would like to thank Peter Brier and Bas van Deursen for giving me the opportunity to be a part of Ultimaker, the company that I desired to work for. You have given me the chance to work in an industry that fascinates me and presents many exciting challenges for the future. Peter, even though our meetings were limited, I thank you for your input and insightful questions that have helped me elevate the quality of this project.

To Jaime van Kessel: Thank you for mentoring me during this project and pointing me to the right people. I appreciate you were always there to help; even when my car batteries died after closing time you put your own hobby project aside to support me. I appreciate your continued efforts in explaining me the inner workings of Cura, the fun conversation and interesting remarks.

To Frederic Meeuwissen, Oscar van de Ven, Aaron Alkemade and Victor van Rooij: Thanks for welcoming me to the Ultimaker family and the numerous lunches we had together. I was sad to see some of you leave before me and you were deeply missed when you did.

To Tobias Hebbink: Thanks for the great discussions during our drive to the Ultimaker headquarters, even though you were sometimes asleep for half of them.

To my mom: Thanks for the many hours spent correcting my work and your support during the final stages of the project. I will make sure to get you something light to read.

Finally, I would like to thank the Cura development team for the continued support that helped me realize this result. I could not have done it if you weren't as welcoming to my questions and took the time to help solve the many issues I had during coding.

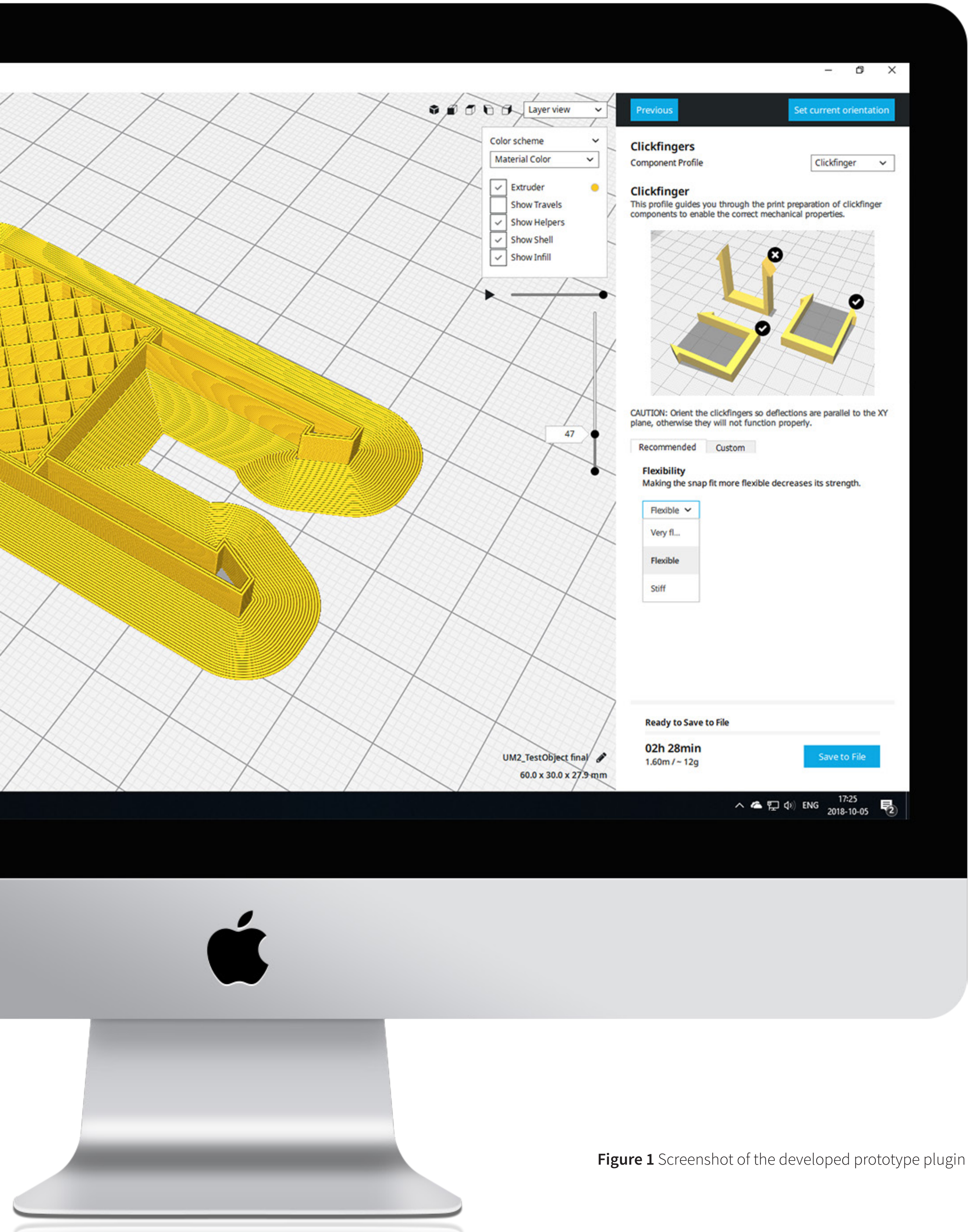
Preface

My name is Joost. I'm a 26-year-old pursuing my master's degree in Integrated Product Design at the faculty of Industrial Design Engineering in Delft. At this faculty I was introduced to 3D printing with Ultimaker printers and I later purchased my own printer. I have not only assembled my 3D printer from kit myself but have also spent increasingly more time understanding the printer through tweaking print settings, calibration, GCODE-manipulation and add-ons in order to get better results. How these machines work fascinates me and therefore I decided to build another, this time from scratch. In my view, 3D printers are part of the next generation of enabling devices which empower professionals in their work, and I want to be a part of this development.

Having developed this fascination for 3D printers, I contacted Ultimaker about doing a graduation project. Ultimaker appealed to me because it is one of the market leaders in 3D printing, developing technical solutions for a seamless printing experience through an interplay of hardware, software and material. This all-encompassing approach attracted me. Moreover, market developments such as removable beds, filament sensors and more powerful processors showed me that this market was, and still is, introducing new possibilities and challenges of both technical and user-centred nature, which I felt eager, and qualified to tackle.

A few years ago, I earned my bachelor's degree in Mechanical Engineering from the Delft University of Technology. However, while I loved diving deep into technical problems until settling on a solution, I found my solutions lacking an essential ingredient. Without taking the user experience into consideration I could never be sure that my designs would actually be used, and consequently, that my work had been fruitful. Therefore, for the past one and a half years I have been expanding my knowledge at the faculty of Industrial Design Engineering where I have applied my technical insights, supplemented with new skills and user-centred design approaches, to create an integrated product.

This graduation project challenges me to put my newly learned user-centred design skills to the test by improving the 3D printing experience.



Clickfingers
Component Profile: Clickfinger

Clickfinger
This profile guides you through the print preparation of clickfinger components to enable the correct mechanical properties.

CAUTION: Orient the clickfingers so deflections are parallel to the XY plane, otherwise they will not function properly.

Flexibility
Making the snap fit more flexible decreases its strength.

Flexible

Ready to Save to File
02h 28min
1.60m / ~ 12g

Figure 1 Screenshot of the developed prototype plugin

Executive summary

This graduation project is carried out as a collaboration between the Delft University of Technology and Ultimaker. Ultimaker B.V. is a 3D printer company located in Geldermalsen, The Netherlands.

Users of 3D printers are presented with a multitude of action possibilities. However, these action possibilities are not yet translated into easy to understand controls that match user intentions. The goal of this project is to design a means for the user to match the intended outcome with the printed result.

Eight design opportunities for intent-based 3D printing approaches are defined based on desk research and user experiments. The desk research focuses on the material extrusion process, the 3D printing workflow, user groups, market trends and intent facilitation techniques. The user experiments analyse the role of user intent in the 3D printing workflow. The eight defined design opportunities are: goal-oriented print preparation, reducing the knowledge threshold, component level control, promotion of 3D printing affordances, management of 3D printers, user education, intent communication and feedback. Ideation is applied to these design opportunities to create three concepts, of which the highest scoring concept is further developed.

The proposed design is a software plugin for the Cura engine based on product configuration systems used in retail. The software architecture consists of six modules that work together to analyse the model geometry, retrieve requirements and wishes based on the communicated intent, recommend profile selections and user actions, validate the print preparation process and guide the user towards ideal printer configurations and process parameters. By using the 3MF file format, models are separated into several components, which can be configured individually by means of 'component profiles'. Component profiles are developed by Ultimaker, companies and individual users to present a subset of print settings that facilitate an intended 3D printed result.

A software plugin for Cura 3.3.1 is developed as a prototype for testing the designed intent-based 3D printing approach (Figure 1). Due to the scope of this research, testing is limited to component-level manipulations and control of goal-oriented settings. From the user test, it can be concluded that print preparation using component profiles significantly improves user guidance and the educative experience of print preparation. Especially beginners are more confident that their configuration leads to the desired part qualities. The objective plugin reduces the feeling of control, but even expert users show confidence in the final result.

Within the plugin users can better voice their intentions through selecting component profiles. These profiles present meaningful feedback to users that both guides and educates them. Of course the realized plugin has its limitations: it does not use intent information that can be included in the supplied model files, nor does it offer all the designed guiding features. Even though these limitations exist, this study represents a step forward in the journey from process-driven to intent-based 3D printing.

Table of contents

1.
Introduction

This chapter introduces the project context, the company involved, and the assignment. This project was carried out as a collaboration between the Delft University of Technology and Ultimaker. Ultimaker has identified that the user experiences difficulties reaching their intended outcome when using 3D printing and likes to investigate new approaches that help users reach their intended results.

1.1
Introduction

The term Rapid Prototyping (RP) was first coined in the 1980's (Huang et al., 2013) when the first technologies were developed in order to produce prototypes for functional testing and validation. Since then, these technologies have matured and the term Additive Manufacturing (AM), also known as 3D Printing (3DP), was introduced (Appendix A), which covers a wide range of technologies.

One of the AM technologies, Material Extrusion (ME) (Paragraph 2.1), also known as Fused Deposition Modelling (FDM) or Fused Filament Fabrication (FFF), has seen a tremendous growth in adoption in both the consumer and professional markets. Since the expiration of the original FDM patent in 2009 (Crump, 1992), a wide range of ME 3D printers have come to the market by both established manufacturers and numerous crowdfunding campaigns. Nowadays, material extrusion 3D printers are used throughout the design process and for local manufacturing of end-use parts.

The widespread adoption of material extrusion 3D printers has yielded a tremendous variety in machine-configurable options, print settings and materials. Faced with this variety of action possibilities, i.e. affordances (Appendix B), during the printing process, there is a need to understand exactly what action possibilities should be taken advantage of in order to meet the users' intent. In this report, intent is defined as: intent is a representation of a combination of actions that an actor or multiple actors may perform in order to achieve a goal. (Appendix C)

Design for Additive Manufacturing (DfAM) identifies two factors that contribute to the user's ability to achieve intended results using AM technologies: “the level of control over the part properties and the level of understanding of affordances” (Doubrovski, 2016). However, linking 3DP affordances to properties of the 3D printed part is difficult. Therefore, this study aims to provide the user with means to better voice his or her intentions throughout the 3DP workflow and to provide the system with means to identify them and present meaningful feedback to the user.

1.2
Ultimaker B.V.

Ultimaker B.V. (hereafter Ultimaker) is a 3D printer company located in Geldermalsen, The Netherlands. The company was founded in 2011 by Sierd Wijnia, Martijn Elserman and Erik de Bruijn subsequent to working together on the development of a 3D printer inspired by the RepRap (Replicating Rapid Prototyper) created by Adrian Bowyer in 2005 (Riley, 2013 & Wijnia, 2015). After publishing their 3D printer design as an open-source project on the internet, people contacted the collaborators in order to buy assembled machines. Overwhelmed by the market demand, the founders decided to create a private company in order to sell the product (Van der Kruit, 2014), and thus Ultimaker was born.

After the success of their 3D printer kit design, the company went from selling build-it-yourself kits towards selling reliable pre-assembled 3D printers (Locker, 2016). The research & development, design, prototyping and testing is all done in-house at Ultimaker's main office in Geldermalsen. Manufacturing takes place in their own factory in Zaltbommel. Nowadays, Ultimaker is considered one of the leading manufacturers in the 3D printing industry (Fisher-Wilson, 2018).

Recently, Ultimaker announced its new 3D printer, the Ultimaker S5, which complements their product portfolio by offering a larger print volume and improved user interaction. Other products in Ultimaker's product portfolio include the Ultimaker 3, Ultimaker 2(+) (and their extended versions), and the Ultimaker Original+. Apart from these 3D printers, Ultimaker sells a variety of 3D printing filaments (materials) and provides an open source slicing software called Cura. These products all commit to the company's mission to accelerate the world's transition to local digital manufacturing. In doing so, the products need to stick to the company's main values: reliable, accessible and leading.

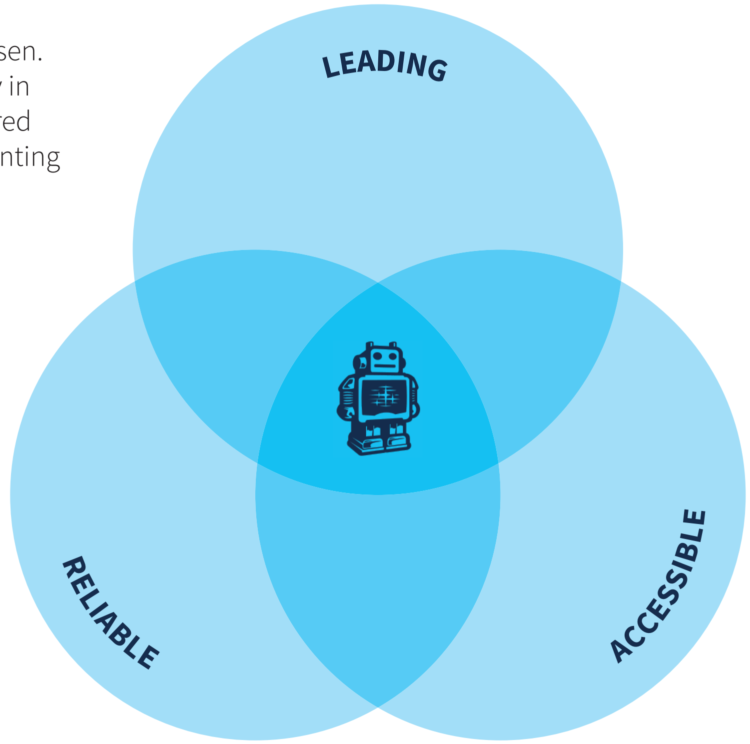


Figure 1.1 Ultimaker's corporate values

1.3

Design brief

The original design brief of this project can be found in Appendix D.

Over the past years of developing material extrusion 3D printers, much of the focus has been on making 3D printing more accurate and reliable. Developments such as variable layer height, multi-material printing and soluble support have brought more options for the user to explore and apply when 3D printing objects. These developments have mainly focussed on the affordances of the material extrusion 3D printer (i.e. the action possibilities made available to the user). The plentiful configurable options available to the user are not yet translated into easy to understand controls that match user intentions (i.e. representations of sets of affordances in the 3D-printing workflow that the user may take advantage of to achieve the intended outcome).

Problem definition

Currently, inexperienced users of 3D printers are presented with a multitude of affordances, ranging from changing machine components (hardware), printing with different materials (material), and fine tuning print settings (software), of which most are hidden at default to avoid misuse. Moreover, preparing prints is process-driven because knowledge of the material extrusion process is required in order to manipulate process parameters to achieve prints with advanced printing requirements. In contrast, intent-based 3D printing could result in a better printing experience and 3D prints that better match the user's goals.

Assignment

The plentiful options available to the user are not yet translated into easy to understand controls that match user intentions. The goal of this project is to identify different user intentions in the context of material extrusion 3D printing and translate these intentions into easy to understand tasks for the 3D printer and its context to perform. Through implementing user feedback, the system can learn a user's goals and meet their intended 3D printed outcome more effectively.

1.4

Thesis structure

This thesis consists of five phases representing the Basic Design Cycle by Roozenburg & Eekels (2003): Analysis, Synthesis, Simulation, Evaluation and Conclusion. The contents of the sections are described below.

Analysis

The analysis phase starts with an overview of the material extrusion process and the affordances offered through 3D printing hardware, software and materials in chapter 2. Next, in chapter 3, the 3D printing workflow is discussed, as well as additional affordances within the different phases of the user experience. Chapter 4 introduces Ultimaker's target group and distills this group into three personas. These personas have different roles in several scenarios in the context in which the Ultimaker printers are being used. Problems that occur in these scenarios, as well as problems due to different customer journeys, are also presented in chapter 4. Chapter 5 discusses the brief history of the desktop 3D printer market, as well as future trends that can benefit solutions for intent-based 3D printing. Additionally, chapter 6 discusses how the analogy between 2D- and 3D printing, as well as intent deduction and intent facilitation technologies can inspire intent-based 3D printing solutions. Chapter 7 concludes the analysis phase with multiple studies on the role of intents throughout the material extrusion 3D printing.

The final chapter of the analysis phase, chapter 8, gathers the information obtained during the analysis phase to form a holistic view of the intent-based 3D printing problem. Therefore, in paragraph 8.1, conclusions from the analysis phase are translated into design opportunities for intent-based 3D printing. Next, paragraph 8.2 presents a design vision for intent-based 3D printing. Finally, the analysis phase is concluded by gathering design criteria that possible solutions should comply with.

Synthesis

Chapter 9 covers the synthesis phase of this project in which ideas are generated to form initial concepts. First, in paragraph 9.1, ideation is performed on How-To questions for each of the design opportunities using the Brainwriting and Brain Drawing methods. The results of this ideation lead to three concepts for intent-based 3D printing that are discussed in paragraph 9.2. Next, a single concept out of these three concepts is chosen as the final design in using the Weighted Objectives method. The final paragraph of chapter 9 presents the final concept by discussing the concept's architecture, user-interaction and visual design.

Simulation

Chapter 10 covers the simulation of the final concept by means of a prototype of the final concept. First, paragraph 10.1 discusses the limitation to the prototype compared to the design. Next, paragraphs 10.2-10.4 discuss how the prototype was made. Finally, paragraphs 10.5 and 10.6 discuss challenges during the embodiment and issues that persist in the prototype.

Evaluation

Chapter 11 presents two user tests that were conducted to validate the design solution, mainly focussing on the user interaction with the product. Several remarks for further improvement of the prototype and the final design are made as a result of both user tests.

Conclusions

Chapter 12, Wrap-up, concludes the thesis with a discussion of the final solution and conclusions regarding its functionality. Furthermore the implications of the design and recommendations for further development are discussed. Finally, a self-reflection of the thesis study is included to reflect on the project process.

2.
Material Extrusion

This chapter investigates the affordances made available through Ultimaker 3D printers, 3D printing software and materials. This chapter aims to answer the following questions:

- How does the technique of material extrusion 3D printing influence the qualities of 3D printed results?
- In what ways can users influence the quality of 3D printed results, given the available affordances of material extrusion 3D printing and specifically the Ultimaker 3D printers and software?
- To what extent are these affordances actually used?
- What challenges for intent-based 3D are implied?

2.1

Material Extrusion

Material extrusion, also known as fused deposition modeling and fused filament fabrication is one of the seven principles of additive manufacturing (ISO 17296-2, 2015). In the material extrusion process, plastic is extruded through a heated nozzle to form layers of material which fuse together by cooling in ambient air (Tempelman, Eyben & Shercliff, 2014). The fused deposition modeling process was invented by Scott Crump in 1992. Later, Crump became cofounder of Stratasys (Perez, 2013) which to this day is one of the leading companies in material extrusion 3D printing and owner of the FDM trademark.

Materials for material extrusion 3D printing come in rolls of plastic, known as filament. The filament is fed through the nozzle using an extruder and is deposited on a (heated) build plate. A heated build plate improves the adherence of the plastic to the build plate and is required for printing some materials. The entire path the filament takes through the 3D printer before it is being deposed on the build plate is called the extruder train.

Extruder (Cold end)

An extruder typically consists of a stepper motor, a drive gear that grips onto the filament and an idler that pushes the filament onto the drive gear. Additionally, the extruder can be a geared extruder, which means that additional gears are added in order to increase the torque on the filament. However, the most major distinction between extruders is whether the extruder is a so called direct-drive extruder or a Bowden-extruder. The difference between the two is that in a direct-drive setup, the output of the extruder motor is directly fed into the hot end, whereas the filament is first fed through a Bowden tube when using a Bowden-extruder.

Hot end

The hot end melts the filament to the printing temperature, which depends on the material. The hot end typically consists of a nozzle, a heater block, a heat break, and a heatsink. The heat break mechanically connects the heater block and nozzle to the heatsink, while at the same time preventing as much heat as possible from transferring to the heatsink. The heater block and nozzle are heated by a heater cartridge and the temperature is measured by a thermistor to allow closed-loop temperature control.

Motion

The hot end is fixed to the printhead, or toolhead (term borrowed from CNC machining). The printhead often incorporates additional sensors and fans used for cooling both the hot end's heat sink as well as the printed part. The movement of the printhead relative to the build plate is controlled in X, Y and Z direction. Depending on the type of machine, the movement in X, Y and / or Z direction is either performed by moving the build plate or the print head. Additionally, the amount of material that is fed through the nozzle, or nozzles if the printer supports multiple extruders, is controlled by the E# axes, where # is an integer count starting at zero. The relative movement in X, Y and Z directions, combined with the amount of extruded material, controls where and how much material is deposited to build a model on a layer-by-layer basis. These movements are controlled by G-code, which is processed by slicing software on a computer. This software will be discussed further in paragraph 3.3 - Prepare.

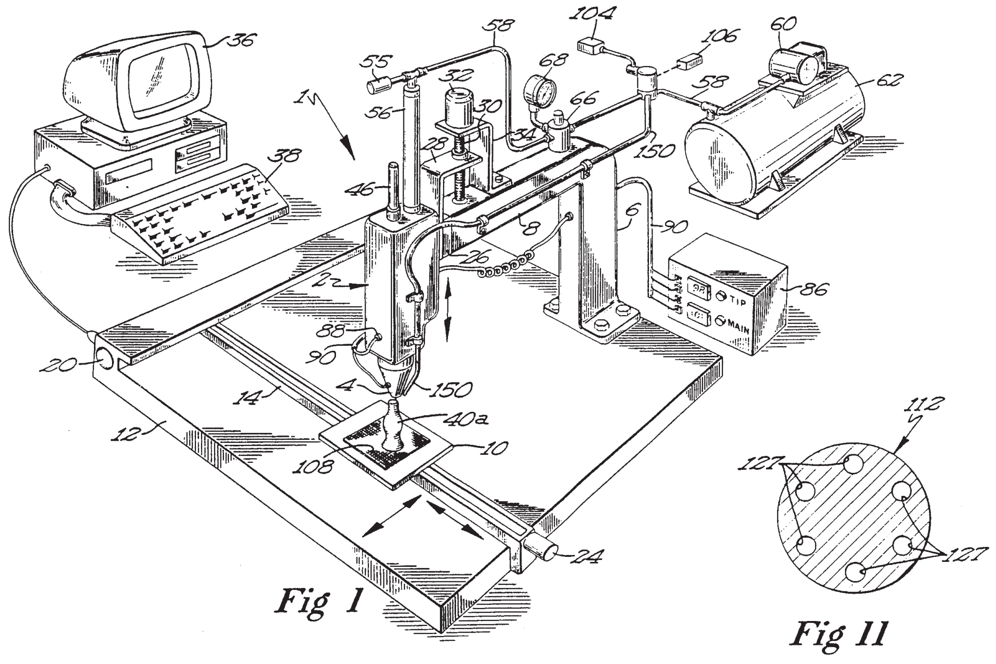


Figure 2.1 Fused Deposition modeling

2.2
Ultimaker 3D printers

Ultimaker printers use the material extrusion process. However, in order to make sure that the printers are accessible, reliable and leading, Ultimaker keeps improving their 3D printers to provide a better user experience. This paragraph highlights some of the major features that were introduced to the Ultimaker 3D printers over the years that distinguish them from the standard material extrusion typology.

Printer portfolio

Recently, Ultimaker announced its new 3D printer, the Ultimaker S5, which complements their printer portfolio (Figure 2.2) by offering a larger print volume and improved user interaction. Other products in Ultimaker's printer portfolio include the Ultimaker
3, Ultimaker 2(+) (and their extended versions), and the Ultimaker Original+. The next paragraphs briefly describe the Ultimaker 3 printers and the recently introduced Ultimaker S5, since these printers introduced the most distinguishing features to the standard material extrusion printer typology.

Ultimaker 3

This section discusses the main features of the Ultimaker 3, the full anatomy of the Ultimaker 3 can be found in Appendix E.

The introduction of the Ultimaker 3 marked a major increase in user friendliness. Since its introduction, it is no longer required to manually level the build platform, as this is now done by means of active bed levelling. This technology automatically levels the bed relative to the nozzle by measuring the inductance between the nozzle and the build platform at multiple points and compensating the z-axis movements accordingly. This ensures better adherence of the bottom layer to the build plate.

Moreover, the Ultimaker 3 introduced a new spool holder design with built-in Near Field Communication (NFC) sensors, that detect Ultimaker supported materials in order to ensure the required materials are loaded. This reduces the chance of failed prints due to the wrong materials being extruded through the nozzles.

Additionally, the Ultimaker 3 comes with Wi-Fi capabilities and a built-in camera to monitor the printing process. But perhaps the most innovative feature of the Ultimaker 3 printers are the interchangeable print cores. Not only does this new design support dual nozzle configurations, but it also makes it easy for the user to change to nozzles with different properties (i.e. material, size, etc.). Additional benefits of the print core design are that the printer is able to detect what kind of nozzles are installed and is able to record data about their use. The next paragraph elaborates on the benefits of the print core design.

Print cores

First introduced in the Ultimaker 3, the print core enables users to quickly change hot ends in order to achieve a higher uptime and more flexibility. Before the print core concept was introduced, changing the hot end of the 3D printer required disassembly of the print head. However, if only the nozzle needed to be changed, the user could disassemble it using a wrench. This process introduced a high risk of damaging other components, especially the fragile heat break. Not only can the user damage other components during this process, but the user also had to make sure to properly (heat) tighten the freshly installed nozzle to prevent leaking. This made the process of changing the nozzle tedious and time-consuming. Instead, print cores use pre-assembled hot end sub-assemblies that make changing a hot end a plug-and play process. (Ultimaker, 2018a) Instead of switching just the nozzle, the entire hot-end is swapped. (Figure 2.3)

Ultimaker S5

The Ultimaker S5 (S stands for studio) is the newest product in the Ultimaker family. As the name implies, it is aimed at the professional office environment. The Ultimaker S5 offers a bigger build volume and improved stepper motor drivers that have improved current control which enables quieter motor movements. Additionally, filament flow sensors implemented in the extruders measure the flow of the filament and are able to detect nozzle clogs and filament runout. Moreover, a new user interface offers friendly touch control and more screen real-estate to inform the user about the printing process, installation and troubleshooting.

Benefits for intent-based printing

The implementation of print cores enables the user to quickly change nozzles for prints with different configuration requirements. This, combined with the new build volume variety, offers users important choices and freedom for achieving their intended 3D printed result.

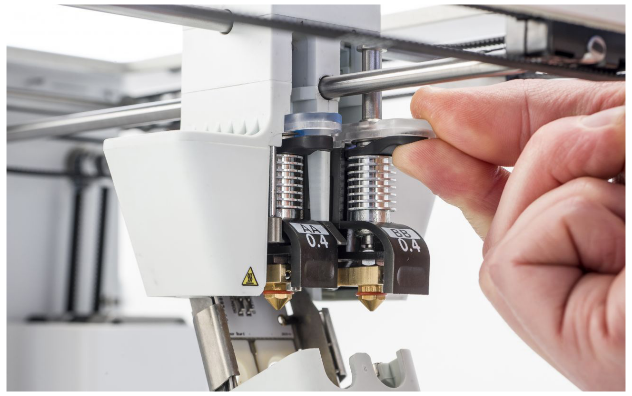


Figure 2.3 Print cores

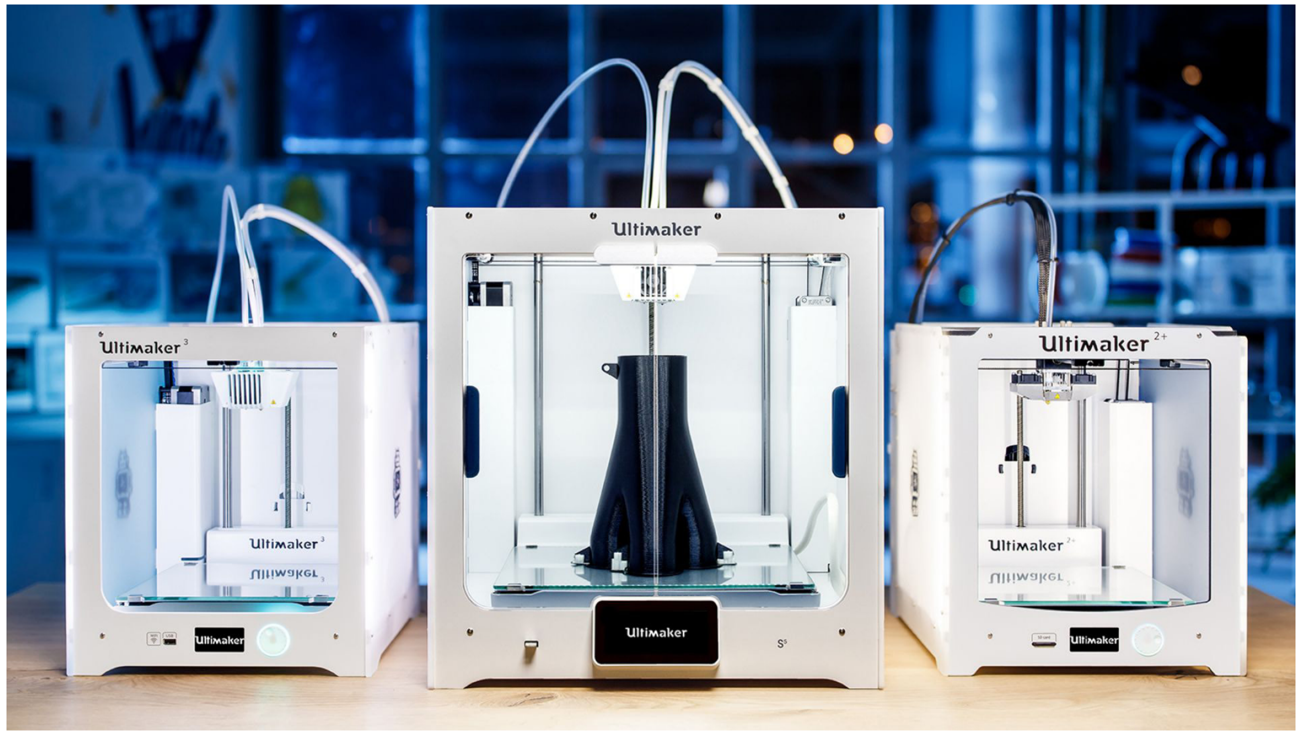


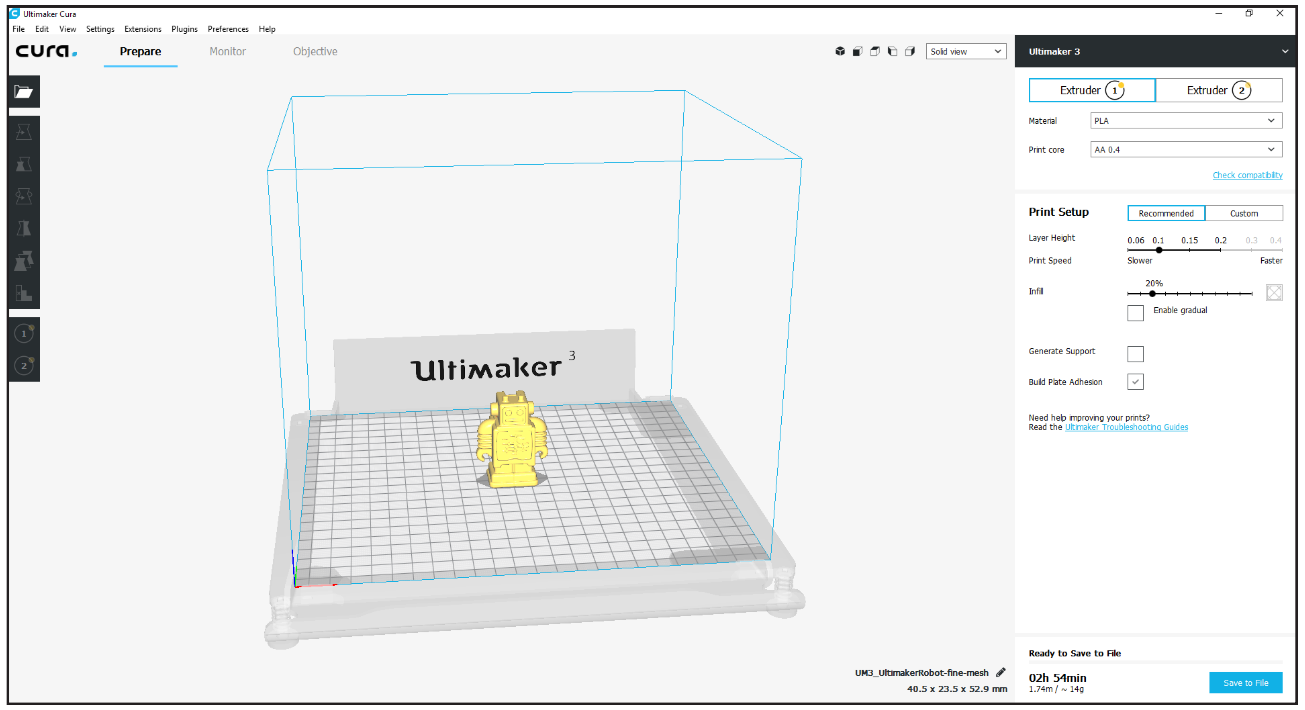
Figure 2.2 Ultimaker printers: Ultimaker 3 (left), Ultimaker S5 (center) and Ultimaker 2+ (right)

2.3
Slicing software

In order to convert Computer Aided Design CAD model from geometry to tool path, specific software is required to translate the model geometry (in STL, OBJ or 3MF format) into a printable G-code file containing the tool path information. This translation is achieved by slicing software, which slices the model into layers based on print settings (hence the name). Ultimaker provides open source slicing software called Cura, but several other popular slicing software packages exist, such as Slic3r and Simplify3D.

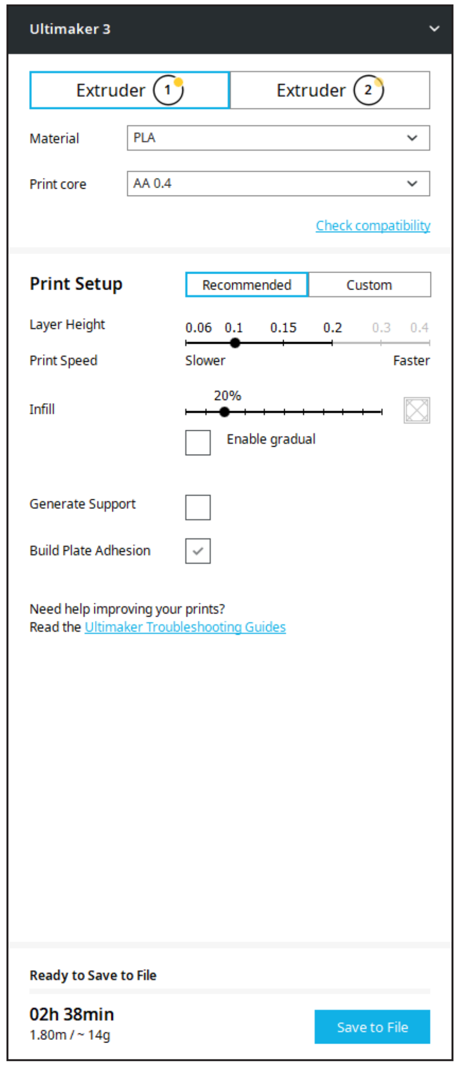
2.3.1. SETTINGS

Cura offers hundreds of print settings that influence the printing process in the sidebar on the right in the user interface (Figure 2.4). Most users do not understand all the available print settings. Therefore, Cura offers users different modes in which to adapt print settings: recommended and custom.



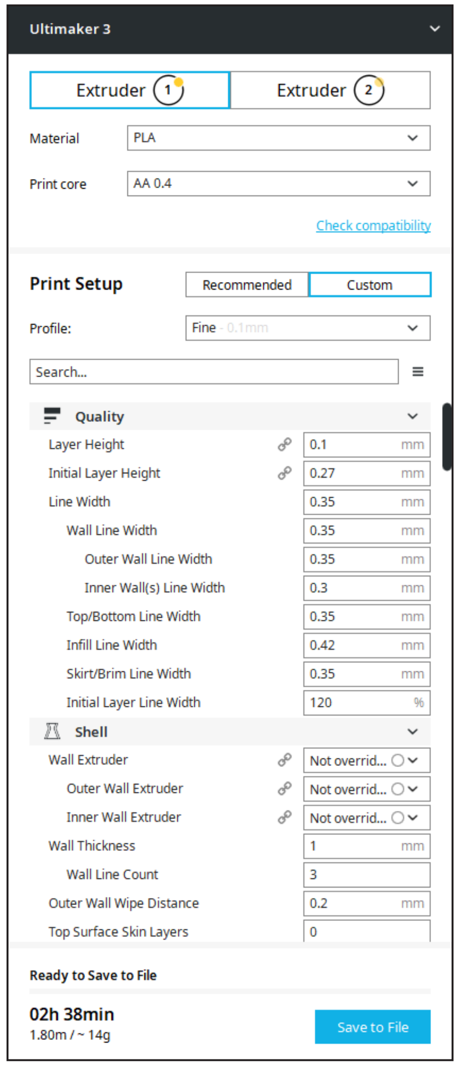
Material: PLA
Print core: AA 0.4
Print Setup: Recommended
Layer Height: 0.06 0.1 0.15 0.2 0.3 0.4
Infill: 20%
Generate Support ☐
Build Plate Adhesion ☑
Ready to Save to File
02h 54min
1.74m / ~ 14g
UM3_UltimakerRobot-fine-mesh
40.5 x 23.5 x 52.9 mm

Figure 2.4 Cura interface



Material: PLA
Print core: AA 0.4
Print Setup: Recommended
Layer Height: 0.06 0.1 0.15 0.2 0.3 0.4
Print Speed: Slower – Faster
Infill: 20%
☐ Enable gradual
Generate Support ☐
Build Plate Adhesion ☑
Need help improving your prints?
Read the Ultimaker Troubleshooting Guides
Ready to Save to File
02h 38min
1.80m / ~ 14g

Figure 2.5 Cura sidebar recommended mode



Material: PLA
Print core: AA 0.4
Print Setup: Custom
Profile: Fine - 0.1mm

Quality	
Layer Height	0.1 mm
Initial Layer Height	0.27 mm
Line Width	0.35 mm
Wall Line Width	0.35 mm
Outer Wall Line Width	0.35 mm
Inner Wall(s) Line Width	0.3 mm
Top/Bottom Line Width	0.35 mm
Infill Line Width	0.42 mm
Skirt/Brim Line Width	0.35 mm
Initial Layer Line Width	120 %
Shell	
Wall Extruder	Not overrid...
Outer Wall Extruder	Not overrid...
Inner Wall Extruder	Not overrid...
Wall Thickness	1 mm
Wall Line Count	3
Outer Wall Wipe Distance	0.2 mm
Top Surface Skin Layers	0

Ready to Save to File
02h 38min
1.80m / ~ 14g

Figure 2.6 Cura sidebar custom mode

Recommended mode

Recommended mode (Figure 2.5) offers the user a very limited amount of print settings, focussing on the most essential ones. The main consideration for the user in this mode is print quality versus print time via slider input. Based on the slider input, Cura automatically switches between predetermined print profiles for various levels of print quality. Apart from this main consideration, the user can set the infill density, add support material and enable build plate adhesion.

Custom mode

In custom mode (Figure 2.6), the user is free to change print settings according to preference. The user can base the print settings on predetermined print profiles, use profiles tuned to their 3D printer or use custom profiles. In addition, the basic, advanced and expert views filter visible print settings according to assumed process knowledge. Print settings are listed under different categories: quality, shell, infill, material, speed, travel, cooling, support, build plate adhesion, mesh fixes, special modes and experimental. Some print settings automatically change based on related settings. For example, print temperature changes automatically when selecting a different material.

Print settings

Cura presents tooltips with descriptions of print settings for both the recommended mode and the custom mode (basic view). These descriptions are aimed to help the user understand what the print setting does and what print settings are related to it. However, there are often no incentives presented to the user to change settings. A notable exception is the layer height setting, which presents the user with reasons to change the setting: increase the setting to lower print time and sacrifice print quality, or vice versa. Instead of merely informing the user what this setting does, Cura tells the user why he or she should or should not change it, and how the user should change it to meet a specific goal.

Another problem is that print settings in slicing software are often controlled by numbers on a continuous scale. However, some settings, such as infill pattern, are presented as a categorical selection. While continuous-scale print settings offer the user freedom and control, they also assume that the user knows the exact influences these scale input values have on the qualities of the printed part.

2.3.2. TOOLS

Apart from print settings, the orientation of the model can influence the model qualities. For example, orienting the model correctly can prevent the need for support material. Additionally, the model orientation can have an influence on other part qualities (see paragraph 2.4). The toolbar on the left in the user interface offers user controls to transform the models on the build plate and assign mesh types in order to communicate to Cura how the slicer should interpret the geometries. The tools available to the user are:

Move tool (also lock)

Enables the user to move models in XYZ direction and lock them into place.

Scale tool (also uniform)

Enables (uniform) scaling in x, y and / or z direction.

Mirror tool

Enables the user to mirror models relative to the X, Y and Z planes.

Per model settings tool

The per model settings tool enables the user to set settings per model by changing the mesh type. There are several mesh types available:

- Support mesh: prints the model as support material
- Cutting mesh: offers a new set of print settings for the overlaps with other models
- Infill mesh: offers a new set of print settings for the infill of overlaps with other models
- Anti-overhang mesh: prevents support material to be printed for overlaps with other models.
- Normal mesh: prints the model normally (default)

Support blocker tool

The support blocker tool creates cuboid volumes through which no support will be printed. These cuboids are simple mesh shapes that can be transformed like normal models. By default these cuboids use the anti-overhang mesh to prevent support material from being printed for overlapping model volumes. However, by changing the mesh type to infill- or cutting mesh, the user is able to overlap parts of models and set different print settings for the overlapping volume. This enables the user to have more control over parts of the model and achieve intended qualities for those parts of the model.

2.3.3. VIEWS

Apart from being able to use the camera, the user can access three different view modes: solid view, x-ray view and layer view (Figure 2.7). Solid view displays the different models in the scene as solid objects and x-ray view enables the user to see planes that are partially occluded by the objects. The layer view mode shows the calculated toolpaths and provides a preview of how the model will look when 3D printed. However, this model preview is limited due to rendering limitations.

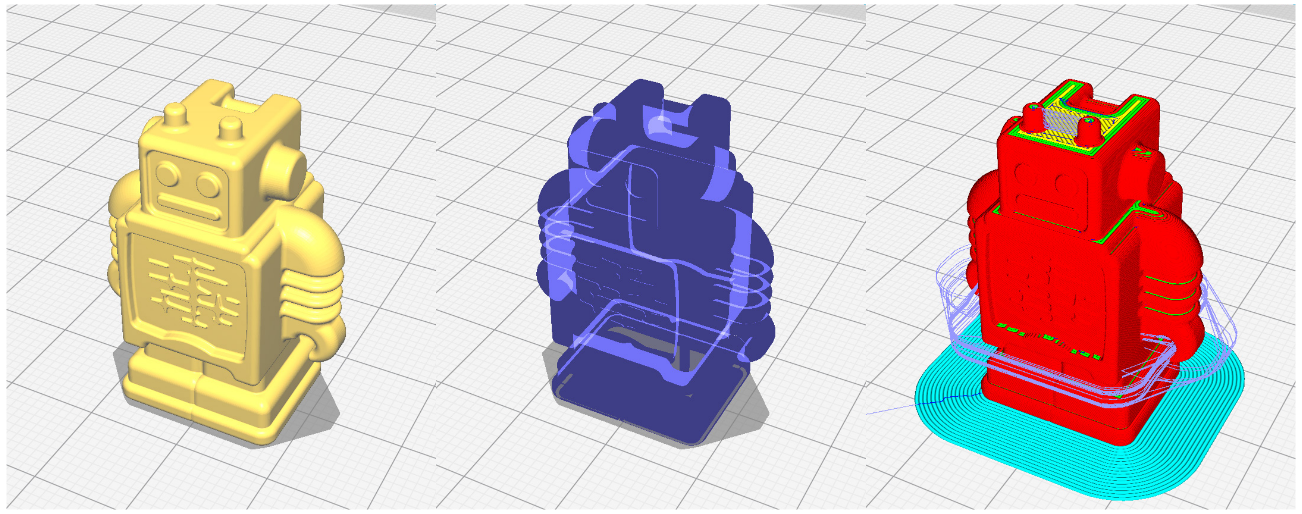


Figure 2.7 Cura views: solid view (left), x-ray view (center) and layer view (right)

2.4

Process parameters

There are several process parameters that influence the resulting part. This paragraph first presents common terms used to describe these process parameters. Secondly, the paragraph presents how these process parameters influence the qualities of 3D printed parts. Finally, the consequences of these influences for intent-based 3D printing are discussed.

2.4.1. MATERIAL EXTRUSION PARAMETERS

The process of building a 3D printed model on a layer-by-layer basis using material extrusion is controlled by several parameters. Some main parameters, as shown in Figure 2.8, are described in Table 2.1.

Process parameter	Definition
Model- or build orientation	“The way in which the part is oriented inside the build platform with respect to X, Y, Z axes” (Mohamed, Masood & Bhowmik, 2015)
Layer thickness	“The thickness of layer deposited by nozzle top” (Mohamed, Masood & Bhowmik, 2015)
Air gap	“The gap between adjacent raster tool paths on the same layer” (Mohamed, Masood & Bhowmik, 2015)
Raster angle	“The angle of the raster pattern with respect to the X axis on the bottom part layer” (Mohamed, Masood & Bhowmik, 2015)
Raster width	“The width of the material bead used for rasters” (Mohamed, Masood & Bhowmik, 2015)
Contour width	“The width of the contour tool path that surrounds the part curves” (Mohamed, Masood & Bhowmik, 2015)
Number of contours	“The number of contours to build around all outer and inner part curves” (Mohamed, Masood & Bhowmik, 2015)
Contour-to-contour air gap	“The gap between contours” (Mohamed, Masood & Bhowmik, 2015)
Perimiter-to-raster air gap	The “gap between the inner most contour and the edge of the raster fill inside of the contour” (Mohamed, Masood & Bhowmik, 2015)
Line width	The width of the material lines used for raster patterns

Table 2.1 A subset of process parameters of material extrusion 3D printing

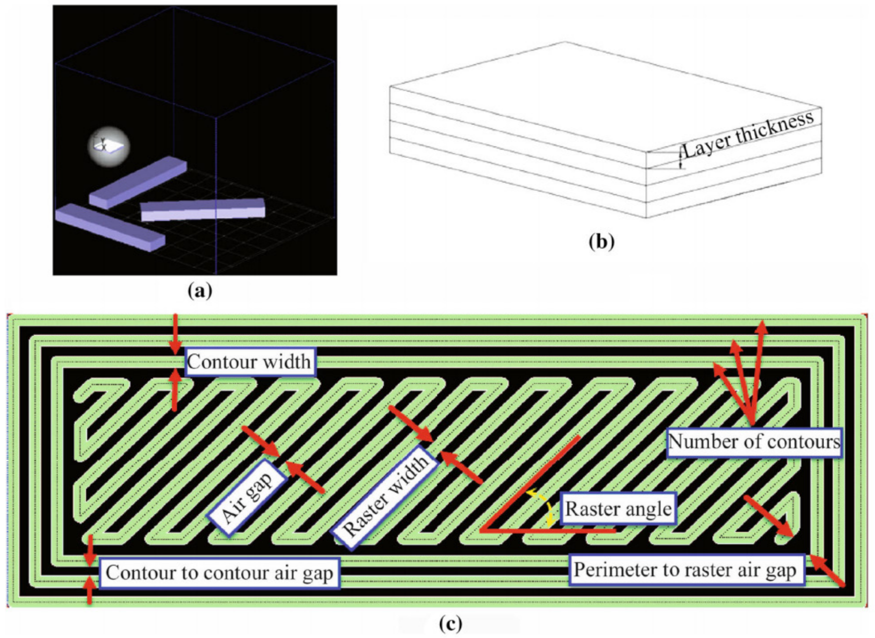


Figure 2.8 a Build orientations, **b** layer thickness and **c** FDM tool path parameters (Mohamed et al., 2015)

2.4.2. PARAMETER INFLUENCES ON PART QUALITIES

Different intents in 3DP are satisfied by optimizing for different part qualities. These part qualities are influenced by print parameters. Therefore, in order to satisfy user intent, knowledge of the relationships between print parameters and printed part qualities is essential. Mohamed, Masood & Bhowmik (2015) reviewed several studies conducted on how material extrusion process parameters influence the qualities of 3D printed parts using ABS material. Parameter influence on part qualities differs between materials, thus the result for ABS may not accurately describe the influences of process parameters for other materials. However, to gain an indication of process influences, these differences are assumed to be minor.

The next sections present how process parameters influence part qualities such as surface roughness, dimensional accuracy, build time, strength and elastic performance. These qualities were selected because research studies on the relationship between material extrusion process parameters and these part qualities was widely available, and because they cover a range of process-, aesthetical- and functional-requirements that users may have when producing 3D printed parts.

Surface roughness

“Anitha et al. (2001) have studied the effect of layer thickness, deposition speed and raster width on surface roughness” (Mohamed, Masood & Bhowmik, 2015). They concluded that layer thickness was a more influential parameter than line width and deposition speed, and that increased

layer thickness has a negative effect on surface roughness. Nancharaiah et al. (2010) support this conclusion, stating that lower layer thicknesses and smaller air gaps result in improved surface roughness. However, an optimum between the influences of layer thickness and air gap combined could not be found due to the research approach.
Thrimurthulu et al. (2004) investigated the influence of model orientation on part surface roughness. They successfully crafted a model to optimize model orientation for surface roughness that can be used to orient any complex model.
Horvath et al. (2007) investigated the influence of model temperature, layer thickness and fill style on surface quality using a factorial experiment design. By varying these parameters, Horvath et al. were able to find a minimum surface roughness of 5.83 micrometers and concluded that high model temperatures lead to smoother surfaces.

Dimensional accuracy

Wang et al. (2007) investigated the influence of layer thickness, deposition style, support style and model orientation on dimensional accuracy. They concluded that orientation and layer thickness influenced the dimensional accuracy. Orientation was of influence on dimensional accuracy due to the different deposition patterns.
Sood et al. (2009) investigated the influence of orientation, line width, layer thickness, air gap and raster angle on dimensional accuracy. They concluded that that shrinkage along the length, width and diameter of a hole fabricated using material extrusion caused both positive and negative diameter variations. This variation could be reduced using a layer thickness of 0.178 mm, 0 degree part orientation, 0 degree raster angle, line width of 0.4564 mm and air gap of 0.008 mm. However, every process parameter had a different optimum.
Nacharaiah et al. (2010) found that air gap and layer thickness significantly influence dimensional accuracy of parts manufactured using material extrusion.
Zhang and Peng (2012) researched the effect of wire width compensation, extrusion velocity, infill speed and layer thickness on dimensional error. They concluded that optimal process parameters for dimensional error reduction were: wire-width compensation of 0.17 mm, extrusion velocity of 20 mm/s, infill speed of 30 mm/s and layer thickness of 0.15 mm.

Build time

Thrimurthulu et al. (2004) developed a mathematical model for optimizing build times based on model orientation and estimating print time. Their results were compared to previously developed models with the same goal indicating similar results.
Additionally, Nancharaiah (2011) concluded that layer thickness and air gap can significantly influence build time. Moreover, Nancharaiah also indicated an optimum for build time using a layer thickness of 0.33 mm, 0.020 mm air gap and 30 degree raster angle.
Finally, Kumar and Regalla (2012) also concluded that both layer thickness and model orientation significantly contributed to minimizing the build time.

Strength

Floor (2015) studied the effect of layer height, print speed, nozzle temperature and model orientation on the tensile strength of 3D printed models. Using an ANOVA method, the influence of print parameters of tensile strength was tested and ranked in order of: fill density, print speed, layer thickness and model orientation.
Floor concluded that layer height has a significant influence on tensile strength. Tensile bars with larger layer thickness had significantly lower strength. Moreover, printing faster also has a significant influence on tensile strength. Higher print speeds cause lower strength and have a more severe negative influence on tensile strength compared to layer thickness. Additionally, print temperature had a significant effect on tensile strength, but with the lowest influence. Objects printed at high print temperatures were found to be stronger.
Model orientation also has a significant influence on tensile strength. It is likely that an increased amount of shell lines in the direction of the force positively contributes to the tensile strength of the object in that direction. Wang et al. (2007) support this presumption, as they found significantly higher tensile strength of FDM parts put in the deposition direction, while the worst tensile strength was discovered in the direction perpendicular to the layers.
Finally, fill density significantly influences the tensile strength of the 3D printed object (Floor, 2015). Increased infill density increases part strength and stiffness. This relationship is not linear, especially at infill percentages above 70%.
Ang et al. (2006) concluded that of the investigated process parameters air gap, raster width, model orientation, and build pattern, air gap has the most significant influence on the mechanical properties of ABS parts.
Sood, Ohdar and Mahaptra (2010) researched the influence of layer thickness, model orientation, raster angle, raster width and air gap on the tensile strength of a 3D printed part. They concluded that thick raster lines and no air gap positively influence the strength of the part. Moreover, they concluded that small raster angles weaken the bonding strength due to residual stresses and deformations.

Elastic Performance

Lee et al. (2006) researched the influence of FDM process parameters on the production of flexible ABS objects. They found that layer thickness, air gap and raster angle have a critical influence on the elastic properties of 3D printed parts (Mohamed et al., 2015). Laeng et al. (2006) found similar results, adding raster width to the list of process parameters that have an important influence on the elastic performance of a 3D printed part of ABS material.

Combined effects

Even though certain relationships exist, the exact influence of process parameters on the end result is still unclear to researchers. This is further complicated by the fact that parameter combinations often have a different optimum compared to the individual parameters. The end-user is struggling with the same unknowns, even on individual parameter basis. In interviews with companies conducted by Doubrovski, participants indicated that “it is well understood that (apart from the designed geometry, chosen AM system, and specified material) the AM process-related parameters influence the final properties of the part. However, how these parameters influence the result is not completely understood” (Doubrovski, 2016). Especially accuracy and reliability require improvement.

Consequences for intent-based 3D printing

The literature discussed in this paragraph shows that different part qualities are influenced by different process parameters. Therefore, a differentiation can be made between process parameters that have a large influence on a certain part quality, and those who don’t. These influences are still not completely understood and hard to determine precisely. This can be further complicated when multiple process parameters are modified at the same time, leading to new optimal values for each of the involved process parameters.

2.5
Material properties

Material selection influences the properties and consequently, the qualities of the printed part. Therefore, material selection is an important consideration to ensure user intent is being met. This section presents how different materials influence the qualities of a 3D printed part.

The material used for 3D printing on FDM machines comes on a roll of extruded plastic string called filament (Figure 2.9). Filament is available in different diameters and amount. Moreover, the consistency of filament diameter differs between manufacturer, as well as the exact material formulation. Ultimaker sells a large variety of materials which have been tested in house in order to provide users with print profiles for reliable use by customers. With these print profiles, customers do not have to change material settings for proper prints, since these are preselected by the software.

Recently, Ultimaker has announced it will be collaborating with global material companies by providing software to generate and maintain print profiles. This collaboration will result in a larger material library with more material variety, providing more options to users to meet their specific material requirements. However, data shows that over 70% of slices made in Cura are for 3D prints with Polylactic acid (PLA) material. While this data does not mean that the sliced models are actually printed, and in what quantities, it does indicate that PLA is still the most popular 3DP material.

Currently Ultimaker sells the following materials:
- Polylactic acid (PLA)
- Acrylonitrile butadiene styrene (ABS)
- Co-polyester (CPE)
- Co-polyester (CPE+)
- Polycarbonate (PC)
- Polyamide (Nylon)
- Thermoplastic polyurethane (TPU)
- Polypropylene (PP)
- Polyvinyl alcohol (PVA)

A full description of these materials and their properties can be found in Appendix G. Due to the limited scope of this project, only the Ultimaker materials are considered in this thesis, because these materials are readily available for testing and offer a more than wide enough range of material properties for the scope of this project.

The different types of materials are the result of different material requirements based on application type. Therefore, the optimal material choice is dependent on user intent. Table 2.2 presents an overview of the main qualities of different materials that may support varying user requirements.

Figure 2.9 Ultimaker silver PLA filaments

Qualities	**PLA**	**ABS**	**CPE**	**TPU**	**Nylon**	**PC**	**PP**
Surface Quality	✓						
Ease of printing	✓		✓				
User-friendly	✓						
Strength	✓		✓			✓	
Impact resistance		✓		✓	✓	✓	
Layer adhesion	✓		✓			✓	✓
Heat resistance		✓	✓			✓	✓
Stiffness	✓					✓	
Durability		✓	✓	✓	✓	✓	✓
Dimensional stability			✓			✓	
Lightweight					✓		✓
Mechnical Flexibility			✓		✓		✓
Elasticity			✓	✓	✓		
Low-friction					✓		✓
Fatigue strenght			✓		✓	✓	✓
Recyclable	✓						✓
Water-resistant			✓				✓
Chemical-resistant			✓	✓	✓		✓
Costs	✓	✓					

Table 2.2 Comparision on filament material properties

2.6
Nozzle properties

Nozzles for material extrusion 3DP vary in diameter, internal geometry and material. These properties affect both what materials are supported in the configuration and the printing process. Therefore, nozzle selection is essential in realizing specific intended results. This paragraph presents how different nozzle properties influence the printing process and the resulting part qualities.

Nozzle material
Most nozzles are made from Brass. However, when printing particularly hard materials, such as carbon filled filaments, the hard particles can cause wear on the nozzle, decreasing its performance over time. Therefore, nozzles from hard materials are also available.

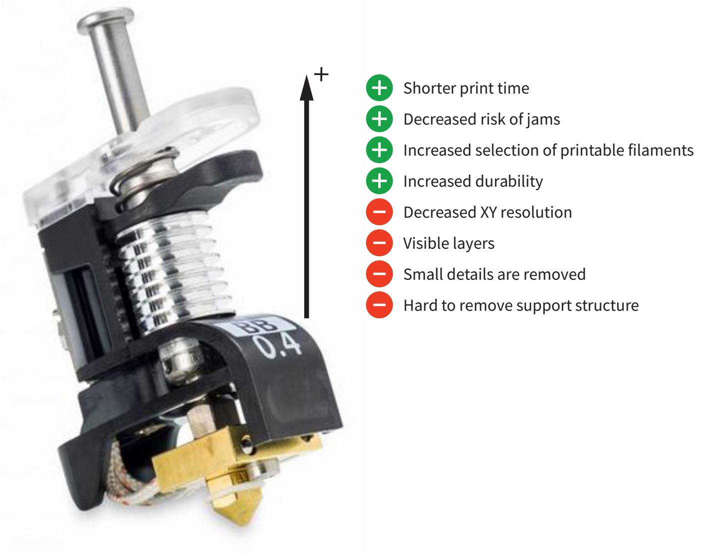


Figure 2.10 Benefits and limitations of increased nozzle size

Nozzle diameter
The size of the nozzle is measured in the diameter of the hole in the tip through which material is deposited. Obviously, the size of the nozzle influences the speed at which material can be deposited. However, while increasing the nozzle size has several benefits, it also has its downsides (Figure 2.10). Due to the increased deposition rate, larger nozzles can print models in shorter print times. Moreover, there is a decreased risk of jams since the dimensions of hard particles in the material are relatively small when using larger nozzles. Downsides of using larger nozzles are the loss of resolution, visible layers and hard to remove support structures. Moreover, small details, such as walls thinner than the nozzle diameter, have a large chance of being removed from the model during slicing.

Internal geometry
The internal geometry has a large influence on the flow of the liquified plastic through the nozzle. This is the main reason why a different print core design, the BB core, is required to print PVA material.

Closing remarks
The nozzle properties have a large influence on the 3D printed part qualities, as well as the printing process and post-processing. Therefore, different nozzle sizes, geometries and materials should be considered during intent-based printing. However, data shows that 97% of slices made in Cura are for the standard 0.4 mm nozzle.

2.7
Conclusions

This paragraph presents the answers to the research questions posed at the beginning of this chapter:

How does the technique of material extrusion 3D printing influence the qualities of 3D printed results?

A lot of research is being performed on the influences of process parameters on printed part qualities. Per quality of the 3D printed object, a selection of parameters can be made that have larger influence on the particular quality compared to other parameters. Predicting the printed part qualities is increasingly difficult the more process parameters are involved.

In what ways can users influence the quality of 3D printed results, given the available affordances of material extrusion 3D printing and specifically the Ultimaker 3D printers and software?

There is a wide variety of filaments and nozzles available for use with the Ultimaker 3 printers. Both have large impact on the qualities and properties of 3D printed parts. Moreover, the Cura slicing engine offers the user a wide variety of settings to influence the resulting outcome.

To what extent are these affordances actually used?

Data about 3D prints prepared in Cura depicts that 70% of the prints is made using PLA material. Moreover, 97% of slices for the Ultimaker 3 are made using the 0.4 mm default sized nozzle. Even though Ultimaker has simplified changing materials and nozzles (via the print core design), users do not often make use of these affordances. Settings in Cura often do not present incentives to change them, requiring process knowledge of the user in order to take advantage of them. Moreover, powerful features in Cura are hard to find, and therefore these affordances are not taken as much advantage of as possible.

What challenges for intent-based 3D are implied?

Challenges for intent-based printing are promoting the use of different materials and nozzles. Moreover, clear incentives should be presented to users to let them know why they should or should not make use of different affordances.

3.
Workflow

This chapter analyses the 3D printing workflow and how it has evolved over time. Moreover, it dives deeper into the affordances available in each phase of the workflow to identify opportunities for intent-based 3D printing. This chapter aims to answer the following questions:

- How has the 3D printing workflow evolved over time and how could intent-based printing evolve it further?
- What are the benefits and limitations of available affordances for intent-based 3D printing in the 3DP workflow?
- What new challenges for intent-based printing can be identified in the 3D printing workflow?

3.1
Workflow

The 3D printing workflow can be divided into four main phases: create, prepare, print and finish. This paragraph briefly describes these phases, how these phases are connected, and how the 3D printing workflow has evolved over time with the introduction of the Ultimaker 3 printer family. Moreover, it presents the opportunities for intent-based printing to further improve this workflow. The next paragraphs present actions that the users may take in order to achieve their intended results in each of these four phases.

Create
The create phase covers the process of designing a model using CAD software. To create a printable model for material extrusion 3DP can be difficult due to the lack of formal design rules (Doubrovski, 2016). The user needs to take the printing process into account when designing models for material extrusion printing to ensure the design is printable. An example of a problem that can occur when a user does not take process parameters into account is object walls being too thin to be printed with the currently installed nozzle. When finished designing the model in CAD software, the model's geometry is exported from the in the .STL, .OBJ or .3MF file format to be imported in a slicing software.

Prepare
Preparing a model for printing in the slicing software is the main task that is performed during the prepare phase. Other actions can include loading different materials, swapping print cores or nozzles, and preparing the print surface. As mentioned, Ultimaker provides the Cura slicing software, but several other popular slicing software packages exist, such as Slic3r and Simplify3D. The slicing software's output is a file containing tool path information that is sent to the printer via SD-card, USB drive, ethernet or Wi-Fi.

Print
The print phase covers the layer-by-layer building process of the 3D print. Apart from troubleshooting when something goes wrong during the printing process, the user can adapt several print parameters via the printer's user interface, such as print speed, material flow, motor mode and z-offset.

Finish
The finishing phase covers every step from removing the 3D printed part from the build surface to the point when the part is considered "done". This process can include the removal of support material (with pliers or by dissolving it in water), sanding, painting, etc. depending on the intent.

Evolution of the 3D printing workflow
As mentioned in the previous chapter, nozzle and material play an important role in the 3DP workflow (Figure 3.1). With the introduction of the Ultimaker 3 and Ultimaker 3 extended, changing materials and nozzles has become easier for the user through the inclusion of NFC sensors and print cores respectively (Figure 3.2). Using the information contained in the G-code, the 3D printer can check whether the right materials and print cores are installed in order to complete the print (1), reducing the margin for error between the prepare- and print phases. Moreover, with the introduction of the BB-type print core and water-soluble PVA material, Ultimaker has significantly improved the post-processing experience in the finish phase (2).

Opportunities for intent-based 3D printing
Several hypothesized improvements that intent-based printing could contribute to the 3DP workflow were a part of the original design brief (Appendix D). Intent-based printing (Figure 3.3) is assumed to be able to further improve the 3D printing workflow in several ways: First, the material and nozzle configuration in the printer could communicate with the preparation process in order to find the optimal configuration as soon as possible (3). Additionally, information from the create phase could be taken into consideration in order to give the user more control of the print preparation process and adapt the model effectively if required (4). Moreover, the intent of the user should be taken into consideration in order to more effectively prepare the model for printing (5). Finally, predicting qualities of the resulting 3D printed objects, as well as using feedback of the (simulated) end result could improve intent satisfaction (6).
Further research is required before being able to judge whether these additions are feasible and indeed improve the 3D printing workflow needs further research. Later sections of this report will discuss the feasibility and effectiveness of these improvements.

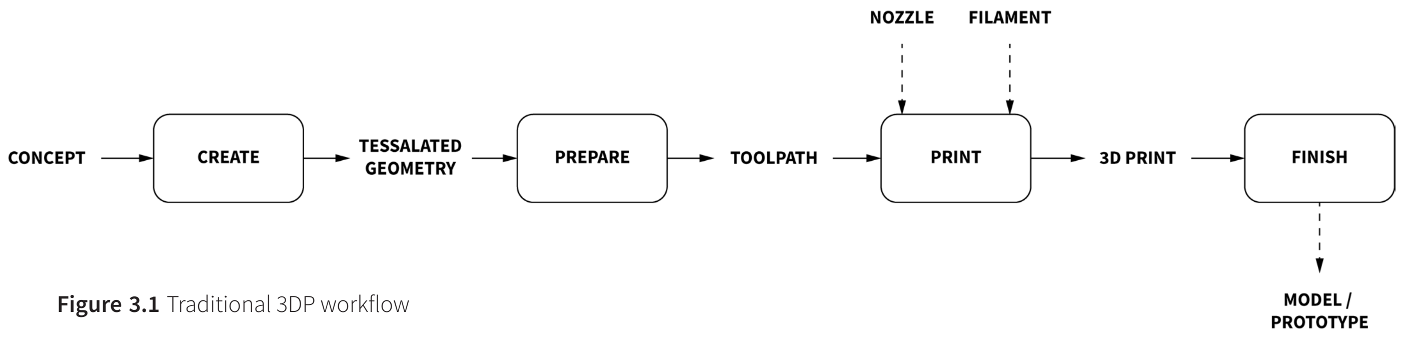


Figure 3.1 Traditional 3DP workflow

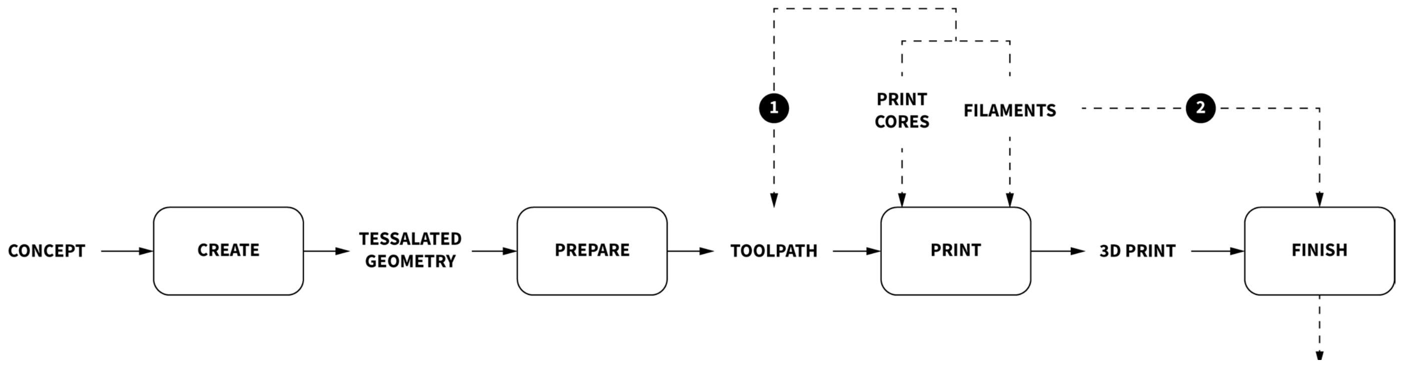


Figure 3.2 Ultimaker 3 and Ultimaker 3 Extended 3DP workflow

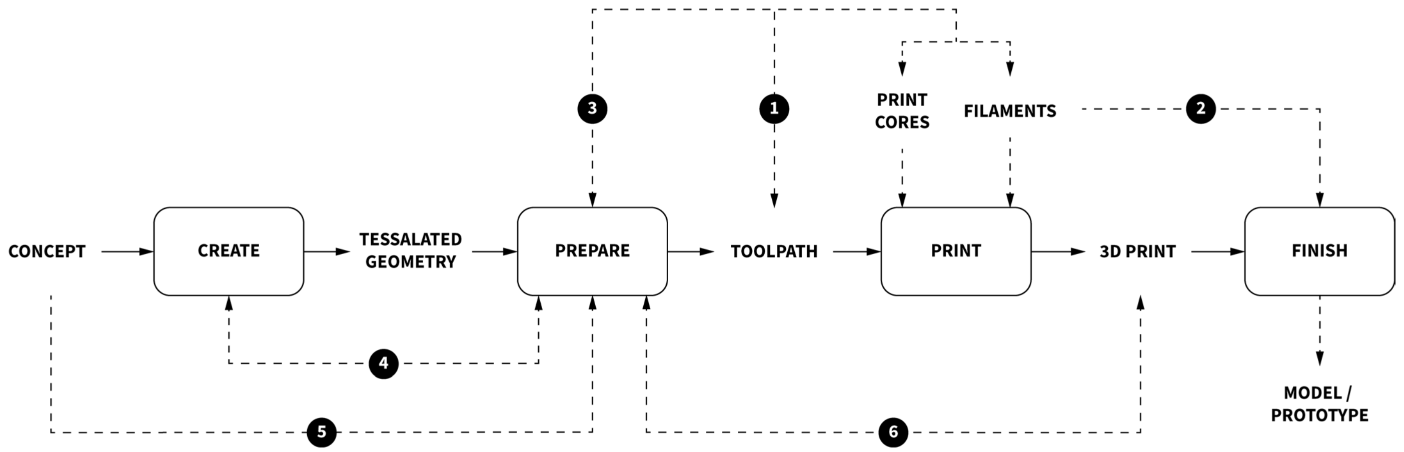


Figure 3.3 Intent-based 3DP workflow

3.2
Create

As mentioned, the create phase covers the process of designing a model using CAD software. In order to take advantage of material extrusion 3D printing, the designed model needs to comply with certain design rules. Some CAD packages incorporate extensions that help the user to follow these design rules, such as the additive manufacturing simulation in Autodesk Netfabb. However, taking advantage of all affordances of material extrusion 3DP might mean that one does not follow the conventional guidelines, but instead explores new possibilities afforded by the process. This paragraph presents how taking the affordances of the material extrusion process into consideration during the create phase can lead to achieving specific part qualities and behaviours.

3.2.1. 4D PRINTING

An approach of taking advantages of the affordances of the affordances of the material extrusion process is 4D printing (4DP). Some user intents go beyond printing merely static parts but require some dynamic behaviour (Figure 3.4). The process of accomplishing these dynamic models is often referred to as 4D printing. Tibbits et al. (2014) define 4D printing as a new process that “entails multi-material prints with the capability to transform over time, or a customized material system that can change from one shape to another, directly off the print bed”. Here, the fourth dimension describes the ability to transform over time, rather than remaining static. Pei (2014) uses a similar definition to Tibbits et al., but does not limit 4D printing to shape change. Rather, Pei also includes chemical and physical change in the definition. Pei (2014) defines 4D printing as “the process of building a physical object using appropriate additive manufacturing technology, laying down successive layers of stimuli-responsive composite or multi-material with varying properties. After being built, the object reacts to stimuli from the natural environment or through human intervention, resulting in a physical or chemical change of state through time.” This report will use the term 4D printing as defined by Pei, since it covers a wider range of dynamically changing part properties.

Figure 3.4 Adidas Futurecraft4D, an application of 4D printing

Metamaterials

As previously mentioned, material selection has a large influence on the properties of the final part. However, the material extrusion process enables new possibilities for materials to be explored, so called metamaterials. Metamaterials distinguish themselves from conventional materials because they do not only inherit properties of their constituent materials, but also from their geometrical arrangement, usually consisting of repetitive cell patterns (Paulose et al., 2015). Since the material extrusion process typically deposes material in lines on a layer-by-layer basis, geometrical arrangement can be controlled in order to form structures with unique dynamic properties. Therefore, 3D printing metamaterials is also considered 4D printing.

Examples of the application of these metamaterials are shown in Figure 3.5. These examples show that the pattern in which material is deposed can influence the mechanical behaviour of a part (Ion et al., 2016), create signalling functionality (Ion et al., 2017) and adaptive surface textures (Ion et al., 2018) and consequently that material extrusion printing can be used to produce parts with intents beyond static behaviour through the application of 4D printing.

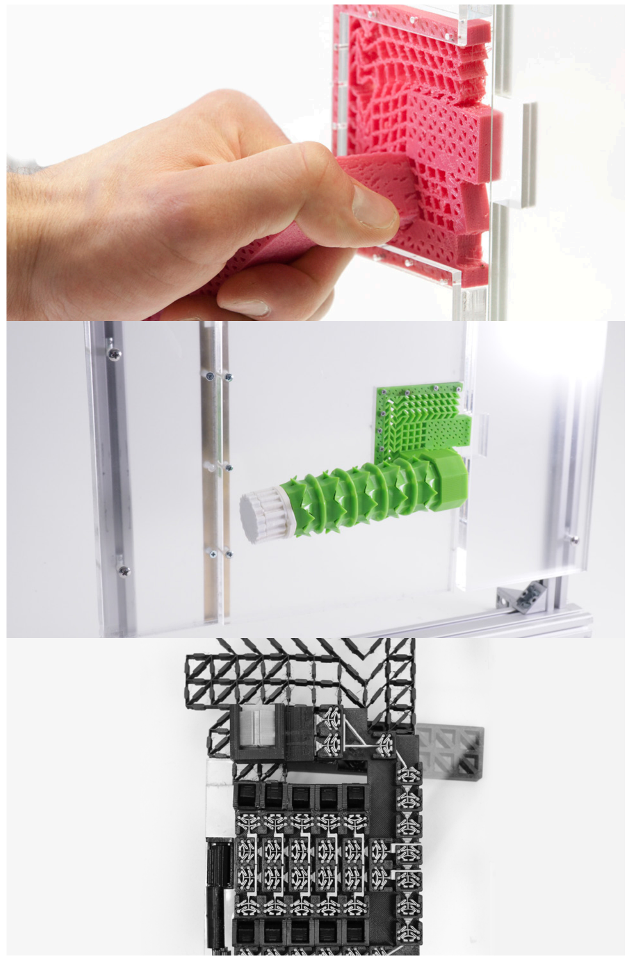


Figure 3.5 Application of metamaterials to enable mechanical behaviour, digital signalling and surface texture adjustment

Figure 3.6 Hairy lion by Primoz

3.2.2. DESIGN FOR POST-PROCESSING

Another approach that takes advantage of the 3DP affordances is to design models for post-processing. In this case, the user takes post-processing into account during the create phase. Examples of a model that leverages the power of material extrusion affordances in post-processing are the Hairy Lion (“Hairy Lion by _primoz_”, 2016) and the Thermorph process developed at Carnegie Mellon University (An et al., 2018).

The Hairy Lion model (Figure 3.6) shows that in some cases altering the model’s shape in post-processing can result in a more beautiful model. In this case, the manes of the lion are printed using the material extrusion bridging capability in order to print straight “hairs”. Bridging is a term used in material extrusion 3DP when a large gap needs to be traversed while deposing material. When doing so, the material needs to be rapidly cooled in order to prevent the material from sagging. After printing, the manes are disconnected from the outer shell that they are connected to and heated using hot air. This allows the manes to be reshaped. Additionally, the manes can be cut to size depending on user preference. The post-processing is performed uncontrolled and every lion will be slightly unique depending on how the manes are reshaped and cut to size.

The Thermorph project at Carnegie Mellon University (Figure 3.7) proves that models can also be designed for controlled post-processing. Like the Hairy Lion model, the parts are designed for post-processing using heat. However, in this case, the part structure is designed in such a way that “designed” internal stresses reshape the model when its heated. The phenomenon of deformation due to internal stresses caused by temperature differences is also referred to as warping, and is mostly considered as a negative influence on the printing process. However, An et al. (2014) use this phenomenon in post processing to deform the 3D printed model through uniform heating. Because of this dynamic behaviour when exposed to an external influence, the Thermorph project is also an example of 4D printing. The Thermorph project shows that by designing shapes for post-processing, complex curved structures can be created without the loss of surface quality due to otherwise necessary support material (An et al., 2018).

Opportunities for intent-based 3D printing

The design of the metamaterial behaviour is complex and often custom designed to certain applications. However, since metamaterials often consist of unit cells that are each designed to achieve a certain mechanical and / or signalling function, there may be applications of infill patterns that facilitate this dynamic mechanical and signalling behaviour. Even though these patterns do not ready for plug-and-play use, they do show that for certain dynamic behaviour it is beneficial to have control over parts of the total model geometry. Therefore, it might be beneficial to the user to be enabled to control model properties on a component basis, rather than a model basis, where the components each represent part of the entire model’s geometry.

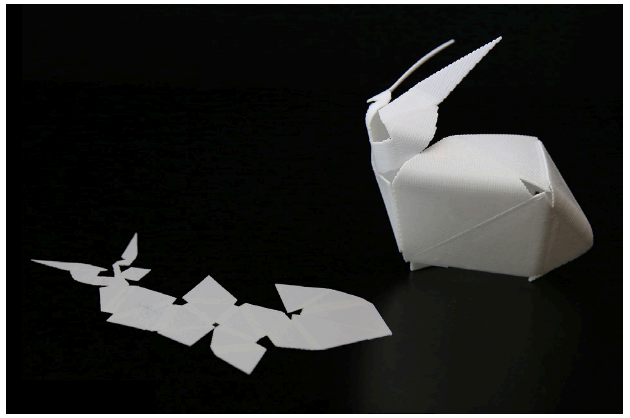


Figure 3.7 Thermorph

3.3
Prepare

As previously discussed, manipulating print settings in the slicing software influences the process parameters that in turn lead to specific part qualities. These print settings are often aimed at manipulating the material extrusion process in ways it is designed to be used: to follow model contours while deposing material, and if required printing infill, support material and bed adhesion patterns. Creative modification of the tool path information in the G-code and addition of extra tool path information during the preparation phase can create models that are otherwise hard to develop in CAD software. This paragraph presents examples of how modifying tool path information and adding tool path information during the preparation phase can lead to specific intended part qualities.

Figure 3.8 Fuzzy skin

Modifying tool path information

Some experimental settings in Cura are good examples how G-code manipulation can lead to better achievement of certain intended results. Two examples are the variable layer height setting and the fuzzy skin settings.

The variable layer height setting allows the user to slice the model with variable layer heights depending on the amount of curvature of the model. Normally, lowering the layer height would lead to increased accuracy for curved shapes and increased print time. By eliminating the extra accuracy in layers that do not require them, the variable layer height offers means to print curved models faster without losing quality. This example shows that using model geometry as an input can, in some cases, positively affect the determination of tool path information for intended part qualities.

The fuzzy skin setting is another example of modifying the tool path information in order to create specific part qualities. In this case, the tool path of the outer contour is modified by a random offset, creating a “fuzzy” look (Figure 3.8). This example shows that specific textures can be created by modifying tool path information, which otherwise would be hard to model in non-surface-modelling CAD software.

Additional tool path information

Through addition of extra tool path information, shapes that are otherwise difficult to model can be printed. An example of such shapes is what Mark Peeters has called “drooloops” (Figure 3.9) (“Super Flowers (drooloop flowers)- customizable by peetersm”, 2014). The name “drooloop” is a combination of the word “droop” and “loop”.

To print drooloops, one needs to deliberately print in the air (hence drooping) and move away from and back towards the model in order to create a loop (hence loop). The drooloops are an example of taking advantage of something that is normally considered a shortcoming of material extrusion: not being able to print steep overhanging shapes without them sagging. Instead of looking at this as a shortcoming, it is considered as a means to 3D print an otherwise difficult to print shape creating a unique intended aesthetic.

Figure 3.9 Drooloops

3.4
Print

During the print phase, users have some control over the printing process. First, the user is able to tune some of the print parameters, such as flow, speed and temperature to adapt the printing process to their needs. Moreover, users can adapt the vertical offset between the nozzle and the print bed to make sure that the first layer of material is deposited correctly.

While changing print speed and temperature has influence on the 3D printed part qualities, they could also have already been accounted for during print preparation. However, a benefit of changing these printing parameters during the print is that the user gets direct feedback of how well the deposition of material matches their intended results. This direct feedback is not available in the slicing software during the print preparation.

Other actions that the user can perform include pausing the print, resuming the print, stopping the print and restarting the print. When the print is paused, the user is able to perform a material change. Some printers, such as the Ultimaker S5, sense that the material supply has ran out through filament run-out sensors and suggest a filament change automatically. However, users can also manually change filament during printing, or pinpoint layers where they want to change material during print preparation, such as through the ColorPrint tool (“ColorPrint - Prusa Printers”, 2018). In doing so, they can create models with layers of different colours, allowing even single extrusion printers to achieve multi-coloured prints without post-processing (Figure 3.10). However, with multi-extrusion printers and multi-material solutions on the market (see Chapter 5), it is likely that these manual filament change interactions will no longer be necessary in the future because they will be performed automatically.

While pausing the print can enable certain actions of the user, such as filament change, stopping the print entirely can provide meaningful information. If the printer is able to measure that the print has been aborted before completion, it could mean various things: the print is unsuccessful, the print does not meet user expectations, the print is no longer necessary, the user has to stop the print due to some external influence, etc. This means that in some cases, this information can be related to how well the user’s intentions are being met, and consequently be of value to intent-based 3D printing.

Opportunities for intent-based 3D printing

While user manipulation of the material extrusion process could be avoided by properly preparing the print, the feedback provided by slicing software is of lesser quality. Therefore, there is an opportunity to implement such feedback in the prepare phase to avoid users having to troubleshoot prints during the printing process. Especially since Ultimaker wants to provide reliable results, even without manual interference.
However, the tuning behaviour of the user, as well as their stop-restart-behaviour, could also be taken advantage of to learn user preferences based on measured user interventions.

Figure 3.10 3D print made using ColorPrint

3.5
Finish

The finishing phase covers post-processing activities that the user may perform in order to reach the intended end result. Some of these post-processing steps are focussed on removing process structures such as support- and bed adhesion material. Other post-processing steps modify the printed part in order to achieve specific part qualities. Some post-processing operations are: support removal, sanding, cold welding, gap filling, polishing, priming & painting, vapour smoothing, dipping, epoxy coating and metal plating (“Post processing for FDM printed parts”, 2018). All of these post-processing actions have unique pros and cons, which are relevant dependent on the intended end result.

Removal of support material and bed adhesion

Removing support and bed adhesion structures from a printed part is a tedious and time-consuming process. Pliers are often used in order to pull the support material from the part. Advancements in materials have led to filaments that are suited for printing as support structures, as these materials are easy to remove in post processing. Examples of such filaments are Ultimaker’s Breakaway- and PVA filaments. Breakaway is very brittle, and therefore easily breaks away from the print part. PVA is water soluble and can be easily removed by cleaning the printed part in water (Figure 3.11).

Figure 3.11 Disolvable support material

Sanding

After removing the support and bed adhesion structures, the model can be smoothed by means of sanding using sandpaper of increasing grit sizes (Figure 3.12). It is best to use wet sanding in order to prevent friction and heat accumulation that can damage the 3D printed part. An additional benefit to wet sanding is that the sandpaper will remain clean.

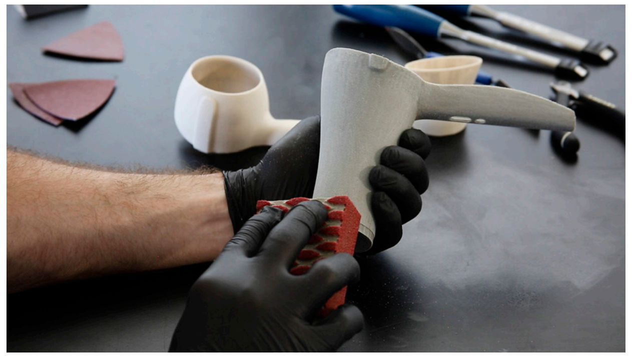


Figure 3.12 Sanding

Cold welding

Cold welding is a means to permanently connect multiple 3D printed parts together (Figure 3.13). This is often required when the 3D model’s size exceeds the build volume. Another method would be to use glue to connect the parts together. However, cold welding results in a stronger bond because the parts are chemically connected together. Unfortunately, cold welding is limited to 3D prints made with ABS filament. By applying acetone on the surface of an ABS part, part of the surface is dissolved. By firmly pushing two surfaces with acetone applied together until the majority of the acetone has evaporated, the parts can be welded together.

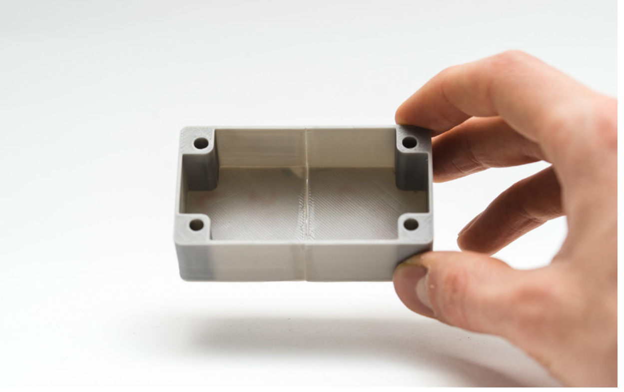


Figure 3.13 Cold welding

Gap filling

Especially when planning to apply glossy paints to the 3D model, visible layer lines and small gaps are emphasized and can ruin the overall aesthetic. These layer lines and gaps in the print, either formed during printing or caused in post-processing steps, can be filled using several products, such as epoxies, wood fillers and filler primers depending on the size of the gap. Most fillers can be applied generously and sanded down to the surface of the print to create a flat surface (Figure 3.14).

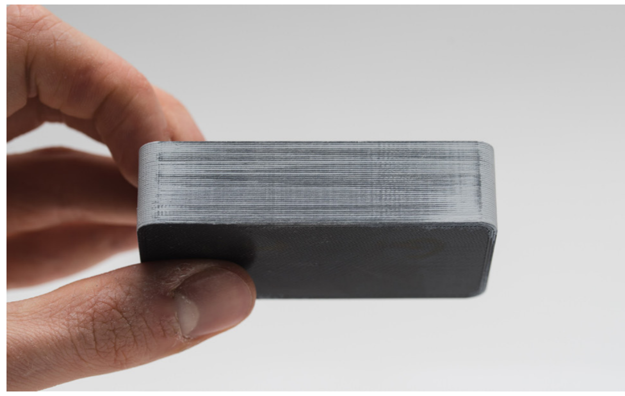


Figure 3.14 Gap filling

Polishing

After a print has been sanded up to 2000-grit, it is possible to polish the surface to achieve a mirror-like surface. Several types of polish are suitable for 3D prints, but some contain chemicals that can ruin the print. The polish can be applied using a buffing wheel attached to a rotary tool, or by using a microfiber cloth.

Priming & painting

An often-used method of post-processing 3D prints is priming and painting. Paint offers a much larger variety of available colours and finishes compared to unprocessed 3D printed filaments. Spray paints are the best option because they can be applied in thin coats to create an even finish. After filling and sanding the 3D print, a primer is applied to ensure the paint will stick to the print’s surface. Subsequent to coating the print with primer, paint can be applied. It is beneficial to apply the paint in multiple, thin layers in a dust-free environment. Because of the multiple coats required, painting can be a lengthy process. However, the result can create professional looking models that mimic a real product’s aesthetics (Figure 3.15).

Figure 3.15 Painting

Vapour smoothing

Vapour smoothing allows the smoothing of a 3D printed parts surface using solvents (Figure 3.16). For parts made with ABS filament, this solvent can be acetone. For PLA, other solvents can be used, but these are generally less effective compared to using acetone on ABS parts. Vapour smoothing can be performed by placing the 3D printed object in a closed container lined with paper towels soaked in the required solvent. However, dedicated smoothing stations are also available for purchase.

Figure 3.16 Vapour smoothing

Dipping

Dipping is similar to vapour smoothing in the sense that it dissolves the exterior material of the 3D print in order to smoothen its surface. However, instead of using vapour, the object is submerged in a liquid solvent (type depend on the material) for a few seconds and left to dry until all the solvents have evaporated.

Metal plating

Metal plating can be performed using electroplating. Before starting the electroplating process, the 3D printed part is coated with a thin layer of conductive paint. In case the part was printed in ABS, a solution of acetone and graphite works as well. The coated 3D print will serve as the cathode during the electroplating process, and is therefore connected to a circuit, typically via a wire, screw or eye hook. Subsequently, the part and a sacrificial metal anode is submerged in an electrolyte solution. Once current is applied to the sacrificial metal anode, oxidation allows metal ions contained in the anode to dissolve in the electrolyte solution. At the same time, a portion of the negatively charged electrons that travel from the cathode to the anode react with the dissolved metal ions, setting them free as metal atoms. These reactions take place at the interface between cathode (3D printed part) and the electrolyte solution, causing the resulting metal atoms to take place on the cathode surface, metal plating it (Figure 3.17).

While this process can be performed at home, deep knowledge of materials and process is required. For this reason, and because what can be achieved with do-it-yourself methods is limited to copper and nickel base plates, it could be beneficial to resort to a professional shop. Professional shops have much more knowledge about the process and have a wider range of plating options available. Like with glossy paints, layer lines and gaps are emphasized on the end result, which can be prevented by properly filling and sanding the model beforehand. After the metal plating is finished, it is recommended to apply a metal lacquer to prevent corrosion.

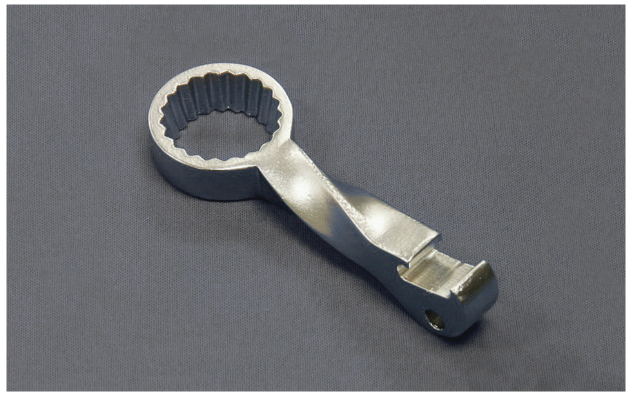


Figure 3.17 Metal plating

Post-processing methods and intent

The different finishing methods presented in this paragraph each provide the user with unique ways of achieving intended aesthetics and material properties. Material selection influences the available post-processing methods, and therefore which intended aesthetics and material properties can be achieved. Moreover, some post-processing processes can not be applied when pursuing certain intended outcomes, since some part properties may suffer negative influences such as altered part dimensions.

3.6

Conclusions

This paragraph presents the answers to the research questions posed at the beginning of this chapter:

How has the 3D printing printing workflow evolved over time and how could intent-based printing evolve it further?

Through the inclusion of additional sensors in 3D printers, the margin or error through user settings is lowered. 3D printers can now sense whether the right materials and nozzles are loaded before starting a print. Moreover, new materials such as water-soluble PVA and breakaway materials have improved the post-processing experience.

What are the benefits and limitations of available affordances for intent-based 3D printing in each of the phases in the 3DP workflow?

Create Phase:
By leveraging the properties of the material extrusion process, material can be deposed in patterns to create structures with specific dynamic behaviour. Moreover, taking post-processing into consideration during the create phase can significantly benefit part qualities. Using uncontrolled- or controlled post-processing, such as heat deformation, can help create structures that are otherwise hard to print.

Prepare Phase:
Some surface textures and features that are hard to model in CAD software can be created through the modification of existing tool path information and the addition of extra tool path information. While these options introduce an alternative way of achieving possible intended results, users tend to regard these affordances as negative, rather than as means to create otherwise difficult to achieve models.

Print Phase:
By tuning a limited set of process parameters, users are able to influence properties of the resulting 3D printed object and gain direct feedback on their adjustments. This direct feedback is not present during current print preparation.

Finish Phase:
The actions available to the user during the finishing phase are limited by the material selection. Moreover, different nozzle sizes may introduce the need for more post-processing effort depending on the intended object qualities. Additionally, some post-processing processes negatively affect certain intended results, such as sanding, which reduces dimensional accuracy. During current print preparation, users are not alerted to these limitations and negative influences to the finishing phase. Users are considered to have this knowledge.

What new challenges for intent-based printing can be identified in the 3D printing workflow?

The development of specific infill patterns that use cell-like structures as found in metamaterials may be an opportunity to facilitate user intentions that aim at dynamic object behaviour. To incorporate such behaviour, the user would need control of parts of the model at a time, rather than control of the complete model at once.

When creating certain surface textures, modifications of- and additions to- tool path information can benefit intended results and therefore the inclusion of such options in print preparation can offer opportunities for intent-based 3D print preparation.

Additionally, inclusion of direct feedback could be an opportunity for better preparation of 3D prints when trying to meet specific intended results. Moreover, the identification of patterns in the user interaction during the print could be used to determine user preferences and as a validation of whether or not the printed object will meet the intended qualities.

Finally, informing the user beforehand on what post-processing steps are available, or using this information as a filter to selectable print settings, can help users better achieve their intended part qualities.

4.
User

This chapter analyses by whom- and in what context the Ultimaker 3D printers are used. Personas are developed based on predefined personas by Ultimaker. These personas act in several 3D printing scenarios and experience different customer journeys. This chapter aims to answer the following questions:

- In what contexts and for what purposes are Ultimaker 3D printers applied by group- and individual users?
- What problems relevant to intent-based printing can occur in these contexts with these users?
- What new challenges for intent-based 3D printing can be thus identified?

4.1
Target group

Ultimaker targets the professional market and consequently, most of their 3D printers are used in a professional environment. Figure 4.1 shows in what contexts the Ultimaker printers are being used. Within these contexts, the Ultimaker printers are used for different tasks. Internal research conducted by Ultimaker divides the use-cases into four applications: rapid prototyping, rapid tooling, rapid manufacturing and lessons. Figure 4.2 shows how these use-cases are distributed.

The predominant use-case for the Ultimaker printer is still prototyping in order to mitigate risks early in product development (45%). This mainly takes place in agile development processes by designers and engineers who want to validate their models before progressing with research and development.

As the print quality of 3D prints and the consistency between 3D prints increase, so does the viability of using 3D printing for manufacturing end-use parts. In manufacturing, 3DP is used by operators for both manufacturing final parts and manufacturing tool aids (20%). However, limitations in mechanical properties in end-use parts is still a barrier for production with 3D printers (Wohlers Associates, 2017).

In education (20%), students and teachers use 3D printers both to learn about the process of 3D printers and to print objects that help students grasp concepts.

Finally, the Ultimaker printers are used by various consumers, which includes “Makers”, that tinker with the 3D printers for hobby projects and fun experiences (15%).

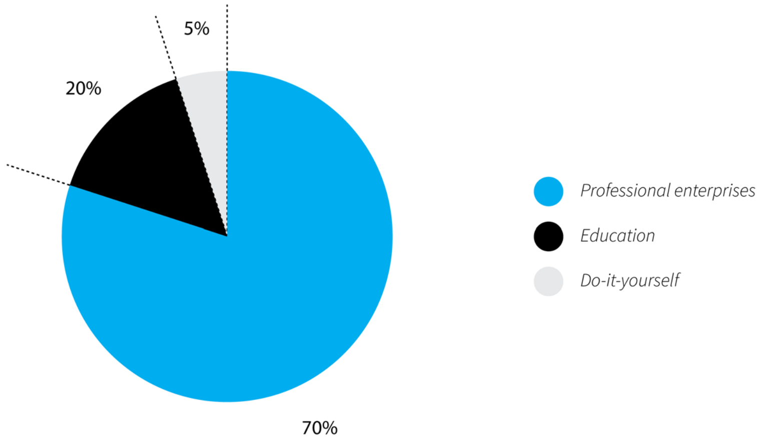


Figure 4.1 Where Ultimaker printers are being used

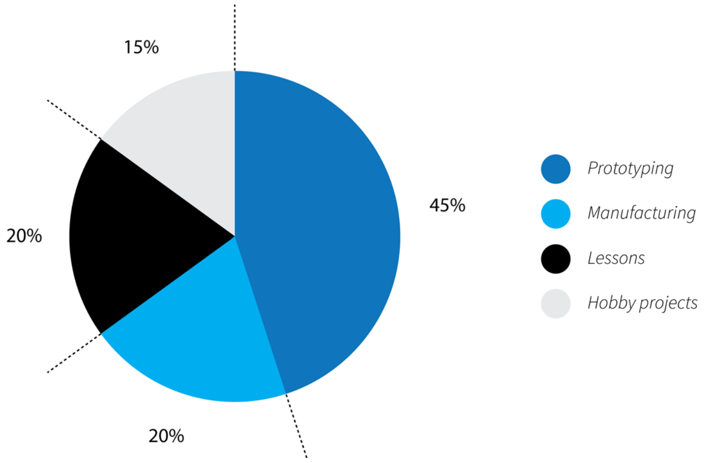


Figure 4.2 How Ultimaker printers are being used

4.2
Personas

Different kinds of users exist within the previously discussed user groups. Ultimaker identifies several different personas that exist within their target group. However, the distinctions between these personas are not always relevant in the context of intent-based printing research. Therefore, new personas are developed which are distinguished by relevant insights for intent-based printing.

From the identified personas by Ultimaker, three personas relevant for intent-based printing are derived: the Vincent (a maker), the Roland (a designer), the Tom (an operator). Both the Vincent and the Roland take part in the creation phase. However, the Vincent has more experience in DfAM. Tom, the operator, is only involved in the creation of the 3D model in an advisory role, mostly focussing on the preparation and print phase of the workflow. These personas introduce themselves in Figure 4.4 on the next page.

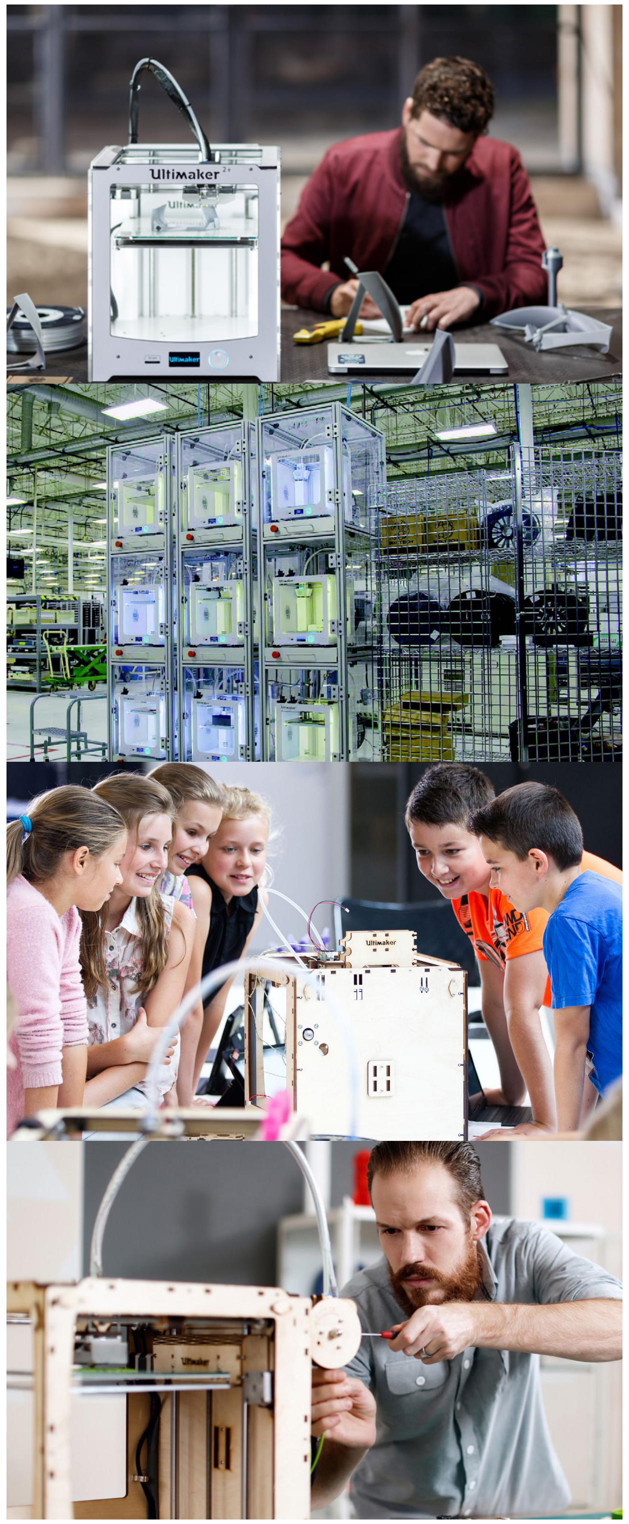


Figure 4.3 Ultimaker printers being used for prototyping, manufacturing, lessons and hobby projects

THE BEGINNER

QUOTE: *“Will I be able to get the desired output?”*

NAME: *Roland*
AGE: *33*
EDUCATION: *Industrial Design*
JOB: *Design Engineer*

RESPONSIBILITIES
My name is Roland, I’m a product design engineer at a small design firm. In my daily workflow, I make lots of prototypes in order to validate my designs and present the design to co-workers and clients. Having a tangible model makes discussions with co-workers and clients more fruitful, and also helps me iterate faster. The prototypes help me find errors early in the design process which helps to eliminate the risks early in the product development. 3D printers offer an exciting new way to prototype my parts instead of traditional prototyping. However, will I be able to use the machine effectively and efficiently?

ANXIETIES
I have little knowledge of the 3D printing process and am therefore afraid that my efforts will be both a waste of time and waste of material resources. I figure that my computer model is printable, is it not? Nothing tells me otherwise. I never know what to expect, because the print settings tell me little about their influence on the end result. Therefore, I still get failed prints without knowing what went wrong. Will I ever be able to put faith into a 3D printer to finish an important job for my next deadline?

PROBLEMS
- *I don’t know what I will get in return; I do not know how the process influences the end result*
- *I am unsure whether the time I invest in printing the model myself is efficient*
- *I don’t know whether my print will be successful.*

THE EXPERT

QUOTE: *“I don’t want to be limited in features.”*

NAME: *Vincent*
AGE: *26*
EDUCATION: *Mechanical Engineering*
JOB: *Engineer*

RESPONSIBILITIES
Hey, my name is Vincent. After graduating cum laude in Mechanical Engineering, I now work at a high-end engineering company focused on cutting edge innovations. 3D printers are great tools in my daily job, because they enable me to make the impossible possible. I can tweak whatever I want and therefore have complete freedom when I want to try out some weird new experimental designs.
In my spare time I like to work on hobby projects. I own a cheap ME 3D printer which I bought from China via Ali Express. I modified it to improve the print quality and add features. Due to my experience with modifying a printer and building the printer according to assembly instructions, I now know everything there is to know about 3D printing.

ANXIETIES
I have been involved in the maker community since the rise of RepRap. The fact that 3D printers are becoming increasingly more high-end also means that I will likely have to pay more to get the latest features in the future. The fact that these systems become increasingly more complex and closed, makes it harder for me to tweak them to my liking.
I hope that some manufacturers will stick to their roots and enable me to change whatever I want.

PROBLEMS
- *I am worried that making a printer more easy to use will decrease its utility because of removed options and closed system nature.*
- *I want to stay in complete control of the process*
- *There are no tools that help me increase my knowledge*

THE OPERATOR

QUOTE: *“I can’t help as much as I would like”*

NAME: *Tom*
AGE: *42*
EDUCATION: *Leidse instrumentmakers School*
JOB: *Workshop assistant*

RESPONSIBILITIES
Hey, I’m Tom. After graduating from the Instrumentmaker School, I am now the king of the workshop at a medium sized company. There is nothing I can’t make! Because the increasing focus on prototyping, I can’t take all matters into my own hand anymore. Luckily, 3D printers can do some of the work for me. I am proud to have a cluster of printer in my workshop, which coworkers can use. It’s painfull to see that most coworkers do not know how to control the settings, causing prints to fail or take insane amounts of time to print. However, I don’t have the time to educate them and once the files are sent, I don’t have the model to adapt the print settings myself. And if I had, I wouldn’t know what to optimize them for!

ANXIETIES
I worry that without the knowledge in 3D printing, my coworkers will never be able to prepare their own projects for printing. The 3D printers were brought in to relieve me of excessive manual labour, but I still end up fixing parts in prost-processing and problem solving coworkers’ failed prints. My boss is expecting the productivity of my workshop to have gone up, but instead I am tasked with more responsibilities.

PROBLEMS
- *I do not know the intention behind the print.*
- *I cannot help as much as I want, because I do not have the project file containing the model.*
- *Some models that I receive need design adaptations. I need to educate the users in DfAM.*

Figure 4.4 Personas

4.3
Scenarios

With these personas, several scenarios can be established in which problems occur during the 3D printing workflow. These scenarios are separated into two groups: individual scenarios and group scenarios. In individual scenarios, a single person, the designer or the operator, is performing tasks in the 3D printing workflow at a time. In group scenarios, multiple persons are simultaneously performing actions in the 3D printing workflow.

4.3.1. INDIVIDUAL SCENARIOS

Individual scenarios can be divided into two scenarios: a scenario with and a scenario without the involvement of an operator.

Single user + single printer

In this scenario, a single user goes through the entire 3DP workflow (Figure 4.5). Thus, the user does not only create the part, but also 3D prints it and takes care of post processing. In this scenario, the designer of the model is not only prototyping the model, but also the printing process. Therefore, the designer gains experience in both designing and 3D printing.

The problems that can occur in this scenario are often caused by a lack of process knowledge. Users with a technical background often unfairly believe they have expert knowledge about the process. This overconfidence can lead to changing advanced settings without the required knowledge. These manipulations can lead to unexpected negative influences on the results. Moreover, while the user does learn from the direct interaction with the process, the lack of feedback of 3D printers makes it hard to pinpoint what settings to change to achieve better results.

Single user + Operator + single printer

In this scenario, two users are involved in the 3DP workflow. A designer, who takes care of creating a 3D model and post-processing, and an operator, who takes care of preparing the model for 3DP and printing it (Figure 4.6). Because designing and printing is separated in this example, the designer is prototyping the model, whereas the operator is prototyping the process. Therefore, the designer is owner of the design experience, and the operator is owner of the process experience.

Problems occur when the designer does not gain the knowledge required to adapt his or her model for 3D printing because process experience is not shared between operator and designer. Vice Versa, problems also occur when the designer does not express the design requirements and wishes to the operator, who consequently does not know what the goal of the print is.

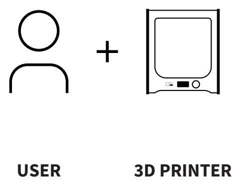


Figure 4.5 Single user + single printer scenario

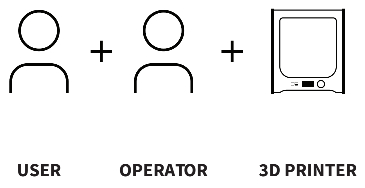


Figure 4.6 Single user + operator + single printer scenario

4.3.2. GROUP SCENARIOS

In scenarios where multiple users use multiple printers it is important to manage print jobs in order to achieve high uptimes. To do so, Ultimaker offers Cura Connect, a software tool for printer management.

Cura Connect

Cura Connect is a software tool that, unlike the name suggests, lives on the Ultimaker 3D printers. It is a tool that enables automatic print job scheduling and management over a cluster of Ultimaker 3D printers. Cura Connect streamlines the 3D printing workflow by maintaining a centralized job list and informing the user which printers need attention. It automatically assigns print jobs to printers with the right configuration of print cores and filaments and the entire system can be monitored via a web interface. (Ultimaker, 2018)

Like individual scenarios, group scenarios can be divided into two scenarios: a scenario with and a scenario without the involvement of an operator.

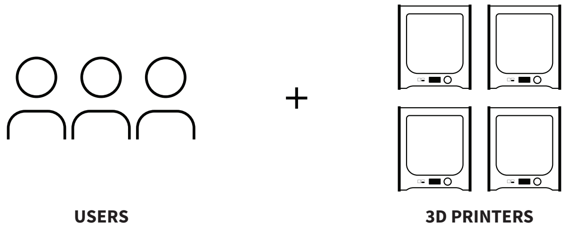


Figure 4.7 Multiple users + multiple printers

Multiple users + multiple printers

With Cura Connect, it becomes easier to control a cluster of printers. This scenario covers the situation in which multiple printers are used by multiple users which go through the entire 3DP workflow individually (Figure 4.7).
Problems that occur in this situation are the following:

- The management of printer configuration is completely free. Individual users who only care about their own print can ruin the plans of others by changing the printer configuration or printing for excessively long times.
- In some cases, printing with a smaller nozzle may be faster than printing with a larger nozzle due to the time it may take to switch between nozzles and the time the user has to wait until the larger nozzle is available. If such possible delays are not clearly presented during print preparation, it is not clear to users what printer configuration will allow the fastest realization of their models.

Additional problems that can occurs when a cluster of printers is not managed properly are discussed in paragraph 5.2.

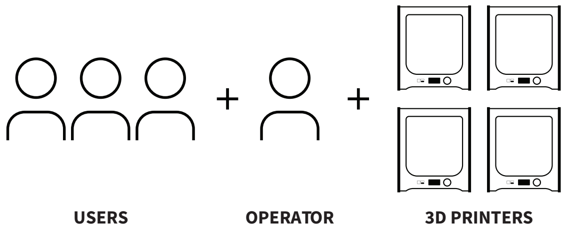


Figure 4.8 Multiple users + operator + multiple printers

Multiple users + Operator + multiple printers

In this scenario, multiple users interact with an operator, who in turn controls a cluster of printers (Figure 4.8). While Cura Connect can automatically distribute print jobs, the operator can overwrite these decisions. Moreover, the operator is directly responsible for the downtime of the printers in the cluster, either due to work schedule or the time it takes to remove a print from the print surface.

This scenario results in situations where users are informed about the print time of their prints, but still have no indication of when the print will be completed due to the possible delay between exporting the toolpaths and starting the print on the machine.

4.4

Customer journey

The customer journey of each of the personas described in paragraph 4.2 is different. While not the entire customer journey has been analysed, the unboxing experience is. The unboxing experience, as described next, is an educative experience designed to inform the user about the different affordances offered by Ultimaker printers.

Education during the unboxing experience

When users receive their Ultimaker 3 series or Ultimaker S5 printers and take it out of the box, they are immediately presented with an educative experience before they are able to start printing. Before printing, users have to decide whether they want to use the AA print core or the BB print core as the second extruder hot-end, since the 3D printer comes with only a single print core pre-installed. As mentioned print cores are available with different nozzle sizes, different nozzle materials and different variants: an AA variant and a BB variant. The AA variant is used for most materials, while the BB variant is required in order to print Ultimaker's water dissolvable PVA filament. Because users need to inform themselves about what variant to use before they start printing, they already learn (1) that print cores are easily interchangeable, (2) how to load a print core, (3) how to remove a print core and (4) that different print cores allow different materials to be printed.

However, in some cases, the user is not the same person who performed the unboxing and initial setup of the 3D printer. Moreover, the user is not necessarily involved in buying materials and nozzles. Therefore, a number of users may not be educated in- and informed about all the options available to them. Since this kind of forced education is not present in the use phase of the customer journey, some users are never properly educated or informed. Therefore, the following problems can occur that limit the user in using all the afforded configuration options to meet his or her intended outcome:

- Users may not be involved in unboxing and initial setup. Therefore, these users may not be informed about the properties of different print cores and the ease with which they can be swapped.
- Users may not be informed about the different nozzles and materials that are available to them.
- Users may not be informed about the properties of different materials that may benefit their project.

This lack of further user education presents an opportunity for additional educative measures to be included in intent-based printing approaches to ensure that users apply the right affordances to meet their intended results.

Figure 4.9 Unboxing experience: installing a second print core

4.5
Conclusions

This paragraph presents the answers to the research questions posed at the beginning of this chapter:

In what contexts and for what purposes are Ultimaker 3D printers applied by group- and individual users?

Ultimaker mainly used in in professional enterprises (70%), but also in education (25%) and do-it-yourself (5%). The four main use-cases are rapid prototyping (45%), rapid manufacturing (20%), rapid tooling (20%) and lessons (15%). The users can broadly be captured by three personas, the beginner, the operator and the expert.

What problems relevant to intent-based printing can occur in these contexts with these users?

- Overconfident users that change advanced print settings without the required knowledge can negatively impact the intended results.
- In scenarios where operators are in charge of (part of) the preparation- and printing process, the designer does not necessarily gain process experience.
- In scenarios where operators are in charge of (part of) the preparation- and printing process, the designer does not necessarily gain process experience.
- Operators can't optimally help designers prepare their prints because they do not receive a model geometry, and if they do, it is hard to derive the intent of the designer. There is no system in place to communicate intents from designers to operators to enable the operator to better prepare parts.
- In scenarios with a cluster of 3D printers, users can ruin the plans of others by changing available print configurations, while taking only their own intentions into account.
- The print time indicated by Cura during print preparation does not reflect when the part is finished, which can be of influence for intents that require fast production of the 3D printed parts.
- Educative experiences are not available to every user resulting in users being unaware of all the affordances available to them and how to take advantage of them.

What new challenges for intent-based 3D printing can be thus identified?

Several challenges for intent-based printing can be derived. The first challenge is the communication of intents between different phases of the 3DP workflow and between the people involved in the 3DP workflow. The second challenge is proper management of 3D printer clusters to reduce the possible negative influences of individual users on the ability of others to reach their intended results. If managed properly, information about available printers, print cores and materials could be used to present more meaningful descriptives about print jobs, such as expected time of completion instead of how long the printing process will take. A final challenge is to incorporate educative experiences for every user, instead of a select number of users that currently come in contact with educative experiences such as unboxing.

5.
Market & Trends

This chapter investigates the market to find influences that are relevant for intent-based 3D printing. Moreover, future technologies that may act as enablers for intent-based 3D printing are presented. Finally, trends in the application of 3D printing are analysed in order to derive knowledge that is applicable to intent-based 3D printing. This chapter aims to answer the following questions:

- What market influences are relevant for intent-based 3D printing?
- How can future material extrusion technologies enable intent-based 3D printing?
- How can knowledge of 3DP application trends be applied to intent-based 3D printing approaches?

5.1

Market

In the early stages of the market development, experts thought that 3DP would change the future of manufacturing rapidly, and like the personal computer, everyone would have their own 3D printer at home. The idea was that consumers would, rather than buy products, make the products themselves using 3D printing. Bre Pettis, co-founder and former CEO of MakerBot Industries, even mentioned back in 2009: “You can make anything you need.” (Zaleski, 2018)

However, in recent years, the market has found out that 3DP is not yet suitable for consumer use. Big players, such as MakerBot, who previously had the vision of putting a 3D printer in every home, are shifting their focus towards the professional market instead. According to Jonathan Jaglom, also former CEO of MakerBot Industries, “the consumer market is ‘just not there yet.’” (Cranz, 2018)

The main issue for consumer use is the supply of 3D models that can be printed. The 3D printer is a hard sell when people do not have a large library of useful models to print, nor the skills to design their own products. However, Mark Palmer, head of experience design at MakerBot, believes that once the process of 3D printing feels less as a chore, the industry might have another chance at the consumer market. Pete Basiliere, research vice president at Gartner, agrees, according to him “consumer 3D printing is around five to 10 years away from mainstream adoption.” (“Gartner Says Consumer 3D Printing Is More Than Five Years Away”, 2018)

The focus towards the professional market is further fuelled by the excessive amount of low-cost 3D printers available in the market. In a market landscape where most 3D printers use similar hardware, software and firmware, manufacturers often compete on price. The average selling price of a desktop 3D printer has continued to reduce to $1094 in 2016, from $1145 in 2015 and $1176 in 2014 (Wohlers Associates, 2017). The average selling price of industrial systems has also decreased in the same years from $104,222 to $97,340 and $87,140 respectively (Wohlers Associates, 2017).

Instead of competing in price, high-end 3D printer manufacturers like Ultimaker compete on value by differentiating themselves from the rest by offering the professional user increased reliability and innovative features. This in turn allows them to compete at higher price points. Additionally, the professional applications for material extrusion printing are evolving and the need for feature rich, production-focussed machines is increasing (more in paragraph 5.2.2).

Material sales

As mentioned, several processes of additive manufacturing exist, of which one is material extrusion. The usage of these processes can be quantified when looking at market numbers for AM materials. Ranked third behind photopolymers (39.0%) and laser sintering (LS) polymer powders (25.0%), filaments used for material extrusion printing contribute 20.4% of the yearly materials market share (Wohlers Associates, 2017). However, considering that the average price per kilogram of filaments is an estimated $25 compared to $60 per liter and $45 per kilogram for photopolymers and LS polymer powders respectively, and assuming minimal differences in weight and density, material extrusion materials are the most bought 3DP material (not including waste).

Implications for intent-based printing

Because most machines use similar hardware, software and firmware, development of intent-based methods for application in the create and prepare phases can be widely implemented across machines.

5.2

Trends

This paragraph discusses the trends in material extrusion additive manufacturing with focus on feature evolution and future application. First, several features that have yet to reach the mainstream but offer new possibilities for achieving intended results are discussed. Next, trends in the application of material extrusion 3DP are discussed to derive implications for intent-based printing.

5.2.1. MARKET TRENDS

Several technologies are in the product pipeline that will influence how users interact with material extrusion 3D printers. Three of these technologies that will have a large influence on how users interact with material extrusion 3D printers are:

- Continuous printing
- Tool-changing
- Multi-material printing

Continuous printing

Currently, printed objects need to be removed from the build plate before the next print job can be started. This has a negative influence on machine uptime. With increasing print speeds, the portion of time lost due to completed prints preventing the next print job from starting grows relative to the amount of time spent printing. Because of this growing problem, and because increases in print speed are progressively more difficult to accomplish, manufacturers take effort in facilitating the experience of continuous printing in order to increase machine efficiency.

Figure 5.1 Mini factory using 3D printers and a robot arm

Different approaches exist to facilitate continuous printing. Some approaches use extra build plates that act as a buffer; while the user removes the finished 3D print from the build plate, the machine can start another print on a new build plate that it retrieves from a buffer. After the user is done removing the print, it can place the emptied and cleaned build plate in the buffer and the process is repeated. The larger the amount of build plates in the buffer, the lower the risk of limited machine uptime. Other approaches are to use a continuous supply of build surfaces or automatically removing prints from the build plate and recycling them through the process. An example of the first solution is to print on a revolving supply band, which can self detach the part (Figure 5.2). An example of recycling build plates is the use of robot arms that retrieve the build plate with finished print from the printer and replace it with a clean build plate (Figure 5.1). Additionally, another machine detaches the prints from the build plate, cleans the build plate and stocks the clean build plates for the robot arm to pick up.

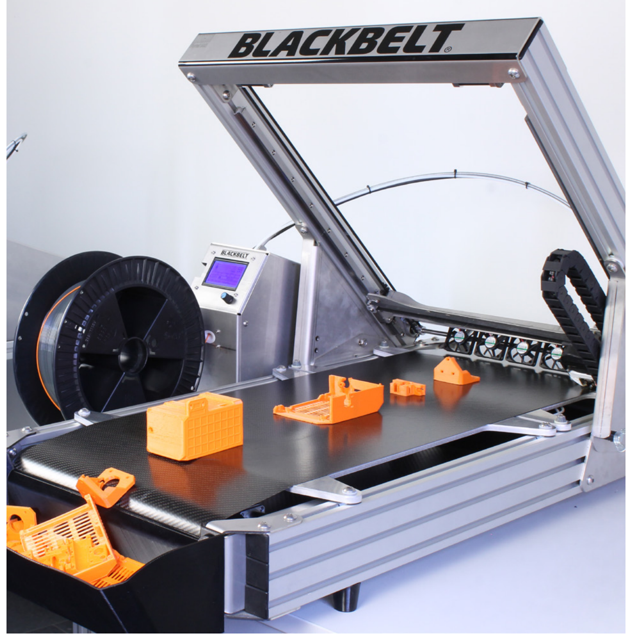


Figure 5.2 Blackbelt printer for continuous printing

The more continuous the printing process becomes, the higher the risk of users becoming alienated from the printing process. Because continuous printing aims to control the process from start to finish, less user interventions are required. Because the user no longer needs to take care of preparing the printer, starting the print job, and / or retrieving the print from the build plate, direct interaction with the printer is limited, and so are the afforded influences towards reaching the intended result. However, the printing process can still be remotely tuned through software during printing, as previously discussed in paragraph 3.4.

Tool-changers

The tool-changer design can be considered an evolution of the print core design by Ultimaker. Rather than making the user change tools - in Ultimaker's case print cores consisting of hot ends with specific nozzles - the machine can pick required tools from a set of parked tools and swap them automatically during print jobs (Figure 5.3).

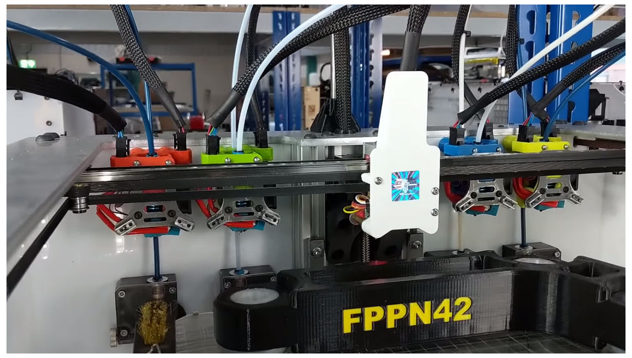


Figure 5.3 E3D tool changer prototype

Benefits of the tool-changer design are ("Post processing for FDM printed parts", 2018):

- Inactive nozzles are parked so they won't influence the print by oozing
- Only the weight of the active nozzle is being moved, resulting in faster printing
- Each material can use its own nozzle which avoids cross contamination and the need for time-consuming unloading and loading processes
- The printer configuration can include more than two nozzles at a time. This increases the number of configurations supported by default and reduces the need for users to change nozzle configuration before printing.
- It introduces the possibility of post-processing tools to be installed without compromising the printing process.

The tool-changer influences the material extrusion workflow in several ways. First, it reduces the need for users to change printer configuration because users can prepare their prints without having to worry about the required configuration being available for use. Second, the fact that the tool-changer can change tools during a print job means that per-layer settings and per-mesh settings do not have to be limited to a single nozzle size anymore. Finally, the ability to change the nozzle during a print job eliminates the limitations that the nozzle introduces to print settings and materials. A tool-changer could pick up the best nozzle to print the selected material along the prepared tool path at any point during the print. So rather than having the user assign the nozzle during print preparation, the slicing software could assign multiple nozzles per print job automatically based on filament selection and print settings.

Multi-material printing

Over the past years, several technologies for enabling users to print with multiple materials have been introduced. These technologies can broadly be distinguished into two categories: technologies for multi-material deposition and technologies for material supply.

Technologies for multi-material deposition
In the past years, several machines have been introduced that use multiple nozzles. These nozzles are either packed together on a single printhead, as is the case with the Ultimaker dual extrusion printers, or installed on separate printheads. Printers that use multiple nozzles installed on a single printhead typically print with only one extruder active at a time and switch between active nozzles. Multi-printhead printers often print with only a single printhead at a time, while the other remains parked on the side. Some multi-printhead printers can print with both printheads at the same time, but this option is generally limited to printing the same object to ensure that the printheads don't collide with each other.

Technologies for material supply

Other technologies deal with the supply of material towards the hot ends, independent on the number of hot ends installed. These technologies can be separated into two categories, mixing extruders and "selecting" extruders.

Mixing extruders are able to continuously feed multiple filaments through a single hot end. By controlling the ratio between the fed filaments, material with varying properties and colour can be blend together. An example of the application of a mixing extruder is the QuadFusion Print head (Figure 5.4).

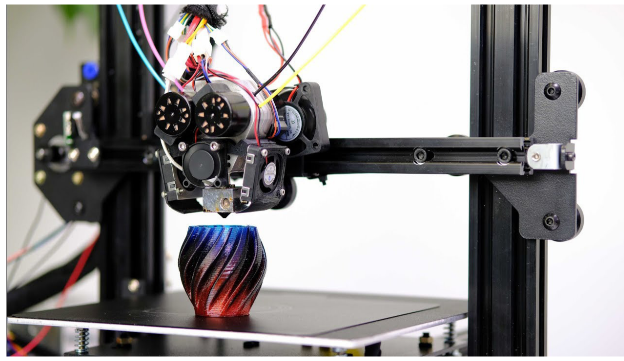


Figure 5.4 The QuadFusion printhead

Selecting extruders increase the amount of filaments that can be fed through a single hot end without manual interference. In contrast to mixing extruders, a selection extruder selects a filament from a set of available filaments and feeds this single filament through the hot end. An example of a selecting extruder is the Multi Material upgrade kit by Prusa Research (Figure 5.5).

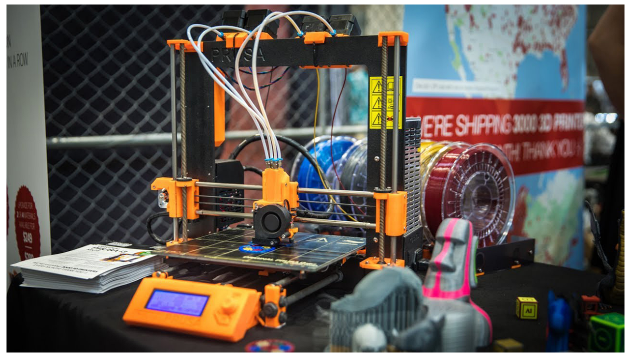


Figure 5.5 Prusa Research's Multi Material upgrade kit (v1)

Implications for intent-based printing

Mixing supplies enable continuous control over material properties such as colour. Moreover, widening the available materials that can be used per nozzle enables the user to use a wide variety of filaments with different properties in a single print, without the burden of having to manually change filaments during the printing process. However, especially with selecting extruders, changing filaments increases print time because the active filament needs to be unloaded, the selected filament needs to be loaded, and the nozzle needs to be primed to ensure that no leftovers of the previous material are deposed onto the print.

5.2.2. APPLICATION TRENDS

According to Wohlers Associates (2017), the segment for producing final parts grew from an estimated $2.65 billion dollars in 2015 to $3.66 billion in 2016, which represents 60.6% of the total product and service revenues of additive manufacturing. According to Wohlers Associates (2017), it is too early to conclude whether additive manufacturing will lead to the next industrial revolution. However, several signs indicate that it might:

- Barriers to enter the product development and manufacturing business are removed
- Additive manufacturing offers a reduction of transaction costs
- Additive manufacturing offers the possibility of decentralizing some types of production.
- Custom product development is increasingly more popular

Because of the growing potential of additive manufacturing it is relevant to look at the development of manufacturing processes and the possible implications for intent satisfaction.

Evolution of Manufacturing

The emergence of the Internet of Things, big data analytics and artificial intelligence have enabled new possibilities for manufacturing. Applying these technologies in the manufacturing industry has led to smarter machines that are capable of addressing current challenges in manufacturing: increasingly customized requirements, improved quality and reduced time to market (Rittinghouse & Ransome, 2016).

Cyber-Physical Production Systems

The increased number of built-in sensors enables manufacturing systems to sense, act-upon and communicate with other systems in their environment (Zhang et al., 2015). These systems merge the virtual and the physical world together and are therefore known as Cyber-Physical Systems (CPSs). The integration of the virtual and the physical creates a single networked world in which intelligent objects can communicate and interact with one another (Lee, 2008). For manufacturing equipment, this merging with the virtual world is referred to as Cyber-Physical Production Systems (CPPSs) (Zheng, 2018).

The widespread application of CPPSs is revolutionizing manufacturing and announces the fourth stage of industrial production, also known as Industry 4.0 (Kagerman et al., 2013). A typical tendency in the product development stage in industry 4.0 is mass personalization (Tsjeng, Jiao & Wang, 2010). Mass personalization is a manufacturing paradigm in which consumers become actively involved in the design process to provide a better user experience and higher customer satisfaction (Tsjeng, Jiao & Wang, 2010). 3DP is a key enabler of this shift towards personalized products.

Smart Manufacturing

Zhang considers CPPSs as smart manufacturing (SM) systems. While no generally accepted definition of smart manufacturing exists, the National Institute of Standards and Technology (NIST) refers to smart manufacturing as a fully integrated, collaborative manufacturing system that responds in real-time to meet changing demands and conditions (Kusiak, 2017). These changing demands and conditions do not only occur inside the factory, as they do with CPPSs, but also in the supply network and in the customer needs. With a growing demand of personalized products, these changes become more difficult to cope with.

Mass customization

The consumer market is moving towards mass customization and personalization and thereby creates the previously discussed tendency that drives industry 4.0. Additive Manufacturing is an enabler of this trend towards mass personalization. An example of a personalizable product that uses 3D printing are Print+ headphones (Figure 5.6).

Since it can be assumed that consumers personalize their products based on and intended outcome, the 3DP industry can take inspiration from current production and how it handles consumer demands in retail. Like a 3D printed model, a customized product is affected by parameter values set by users based on their intentions. The 3DP workflow can therefore be compared to the shopping experience. In 3DP, the “customer” sets the parameter values in the slicing software, in this case Cura. In online stores, these parameter values are often set in a product configuration system.

However, there are also key differences: online stores struggle with getting the right manufacturing in place in order to facilitate the growth of customization options. Moreover, rather than making models from scratch (constructive), as is done by engineers for 3DP, customized products are built from base products which are adapted according to user preference (adaptive). Ironically, the problems in the 3DP workflow are opposite to those in retail: flexibility in production is a key benefit of 3DP, while the translation of user intent towards an end product is problematic. Therefore, it is likely that 3DP can learn from intent-based configuration systems applied in shopping experiences.

Implications of CPPSs on intent-based printing

Looking at material extrusion 3D printers as CPPSs offers new possibilities for how the user is able to realise intended results. By using external information about project progress, the 3D printer as CPPS could adapt the material extrusion process parameters.

Figure 5.6 Print+ headphones

Implications of smart manufacturing on intent-based printing

Smart manufacturing deals with the changes in conditions and demands of the user. These changes in conditions and user demands are also relevant for intent-based printing and become apparent when considering a cluster of 3D printers inside a company as a mini production line. This mini production line does not only need proper management to maintain high machine uptime, but also to ensure that intended 3D print qualities can be achieved within certain timeframes. Examples of changing conditions of this production line are the available filaments, the available (unused) nozzles and the available printer configurations. Additionally, examples of changing demands for this production line are the amount of print jobs company employees are sending, and what configurations are required for the job. These are all important factors that set limitations on how well intended part qualities can be achieved, since:

- Available filaments dictate the limitations of material properties that can be achieved in 3D prints
- Available nozzles determine the limitations to process parameters that can be used during printing
- Available printer configurations dictate in what timeframe the print job can be started and in what size objects can be printed

Additionally, improper management of material supply, nozzle supply, print job order, and printer configurations can lead to several additional problems, such as:

- A print job without specific material requirements can be started without changing the currently installed filament, which may be the only filament that meets the requirements of a print that is due to start at the same time on another machine.
- A print job that is intended to be printed quickly using a 0.8 mm nozzle may be quicker to produce on a machine with 0.4 mm nozzle depending on the wait time until 0.8 mm nozzles are installed and ready to be used (as previously mentioned in paragraph 4.3).

The example of the mini production line inside a company illustrates that the management of print jobs on a first-come-first-served basis may have negative influences, and set additional limitations on the realization of intended part qualities. Therefore, it is beneficial to apply knowledge about smart manufacturing systems for proper management of 3D printer clusters to ensure intent satisfaction. Especially since market transitions to in-house local manufacturing increase the popularity of these kinds of mini production lines.

Implications of mass customization on intent-based printing

Mass customization can lead to parts of a model being customizable which in turn influences how users control their intended outcome. For instance, assume a model that can be divided into several components, each representing a part of the total model's volume. If the model is customizable, the user may modify these components or interchange them with different component variants. As these components change based on user goals, so may the process parameters that can achieve the intended result. Additionally, process parameters of other components may need to react on the modification made to other components. This example indicates that product customization raises the need for component-level control of process parameters in order to achieve intended product qualities.

5.3
Conclusions

This paragraph presents the answers to the research questions posed at the beginning of this chapter:

What market influences are relevant for intent-based 3D printing?

Due to the number of available machines that use the same open-source software and firmware, development of intent-based approaches for implementation in the create, prepare and finish phases of the 3DP workflow can benefit a wide range of consumers. A number of machines use similar hardware inspired by open source projects, but implementing a hardware solution will require more adjustment to specific variants of the hardware.

Additionally, the increased application of 3D printing in manufacturing could draw more attention towards intents related to manufacturing processes that produce 3D printed products.

How can future material extrusion technologies enable intent-based 3D printing?

- In the future, direct interactions with the printer may be limited to an increasingly more closed print phase.
- The development of mixing extruders suggests a future in which the user has more continuous control over material properties
- Increasing the amount of available materials per nozzle through selecting extruders enables users to use a wide variety of filaments with different properties in a single print, without the need of manual filament changes during the printing process.

How can knowledge of 3DP application trends be applied to intent-based 3D printing approaches?

- By using external information, the 3D printer as a CPPS could adapt the material extrusion process parameters.
- Applying knowledge from smart manufacturing systems on 3DP printer cluster management and consequently taking changing demands (3D prints and their intended qualities) and conditions (material, nozzle and printer availability) into consideration can positively affect intent satisfaction.
- Product customization increases the need for component-level control over model during print preparation.

6.
Facilitating intent

This chapter analyses the analogy between 2D- and 3D printing to learn how knowledge of intent-based 2D printing can benefit intent-based 3D printing. Moreover, non-printing applications and technologies are investigated to learn how to facilitate user intents. This chapter aims to answer the following questions:

- What can be learned from intent-based 2D printing and from intent-facilitation in non-printing applications to improve intent-based 3D printing?
- What can be learned from patents on user intent recognition in different product contexts to improve intent-based 3D printing?

6.1
Analogy between 3D- and 2D printing

Of course, people are not unfamiliar to processes that enable them to turn virtual objects into physical products. People have been printing in 2D for years and have grown accustomed to this interaction. It is beneficial to compare how the 2D printing workflow ensures that people achieve satisfactory results to how the current 3D printing workflow does, because 2D printing has achieved what is desired for 3D printing: beginners can just hit 'print' to get satisfactory results, while advanced users have advanced control over the printer output.

2D printer management
The technological developments in material management in 3D printers (as discussed in paragraph 5.2) attempt to achieve near continuous printing like 2D printers do. The material supply of inkjet printers consists of buffers of ink and paper. Professional printers differ from desktop variants in the ability to stock several different paper types of varying material and size while desktop variants are often limited to a single paper tray. The multiple trays are an example how the hardware is designed to support multiple intents without user interference.

How 2D printing satisfies intended results
In 2D printing, a major problem when it comes to reaching intended end results is the disconnection between the colours that a user sees on screen and what he gets from a printer. Because monitors and printers use different colour spaces, RGB and CMYK respectively, there is a difference in colour compatibility between the two; some colours that can be displayed in RGB colour space cannot be reproduced in CMYK and vice versa. Moreover, not all screens and printers are able to reproduce the entire colour range available to their colour spaces, because their supported subset of colours, or gamut (Figure 6.1), is limited not only by colour space, but also by output hardware limitations.

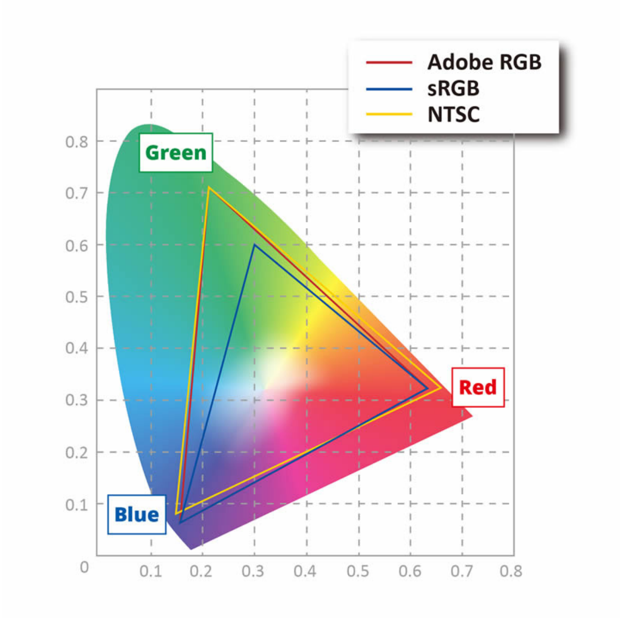


Figure 6.1 The Adobe RGB, sRGB and NTSC gamuts

In order to solve the differences in supported gamuts of different devices, ICC profiles are used. An ICC profile characterizes a colour input or output device by a colour space according to standards by the International Color Consortium (ICC) ("ICC profile", 2018). They define a mapping between the device source or target colour space and a profile connection space, allowing every device that supports ICC profiles to display the same colours in theory.

However, as mentioned, in practice the gamut of screens and printers is limited by colour space and output hardware. Therefore, ICC profiles commonly contain several mappings for different rendering intents that define how the colour reproduction process should reproduce an image when using an ICC profile, and importantly cope with colours and tones which are outside of, or near the edge of the device's colour gamut, in order to achieve the desired colour 'rendering'.

Four rendering intents commonly supported by ICC profiles are:

1. Colorimetric: Colorimetric rendering intents aim to map colours as accurately as possible. However, this may result in some colours outside of the supported gamut to be replaced by the same colour which results in loss of detail. The mapping is either relative to paper white (absolute colorimetric) or relative to the white-point of the original file (relative colorimetric). ("Adobe Acrobat Color settings", 2018)
2. Black point compensation: Black point compensation maps the black-point of the input profile to the black-point of the output profile to compensate the often darker colours produced by printers. ("Colour Management - How it works", 2018)
3. Perceptual: This attempts to present colours in a way that is natural to the human vision ("Adobe Acrobat Color settings", 2018). It moves out-of-gamut colours to the closest in-gamut colours, while preserving the relationships with other colours in the image.
4. Saturation: This will increase colour saturation by pushing colours to the edge of the gamut, resulting in stronger colours. ("Colour Management - How it works", 2018)

These rendering intents present additional modifications to how points of colour are modified towards user preferences. Before preparing for print the user has already defined a target colour. The rendering intent is only influencing how the printer adapts if this target colour can't be accomplished. In current 3D print preparation with .STL files, there is no information about the target property values and consequently a similar approach with rendering intent cannot be used.

Full colour (half toning)
Full colour is a printing technique that can reproduce the full range of colours available. The full-colour range is achieved by printing various amounts of a four colour set: Cyan, Magenta, Yellow and Black (CMYK) (Soto, 2013). Halftoning is commonly used in full colour printing to create different shades of colour by varying the density of these four used inks. The density of the four colours can be achieved in different standardized dot patterns which results in the dots forming small circles or rosettes (Figure 6.2). While the user has control over these process-parameters, the control is presented in a meaningful way. Users control the result, rather than the process parameters that enable that result to be realized. However, in 3D printing, the user controls the process parameter, often without a representation of the result. For example, the strength of a part can be influenced by infill density, but users have no representation of how much the strength of a part changes when the infill density is increased by 10%.

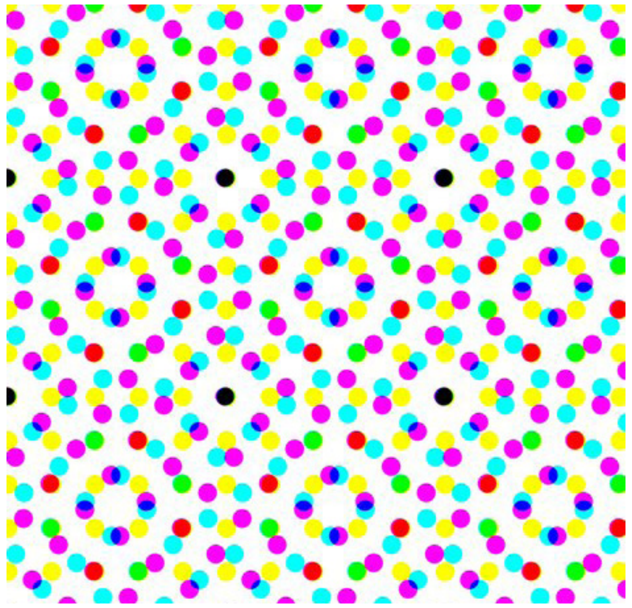


Figure 6.2 Halftoning in full-colour printing

Halftoning can also be used to create greyscale images (Figure 6.3). Similar techniques are being developped for material extrusion 3D printing. For example: Kuipers et al. (2018) use line-based halftoning to produce 3D objects with the appearance of full greyscale imagery (Figure 6.4), indicating how affordances of 3D printing can be used in more advanced manners to satisfy aesthetic intents.

Figure 6.3 Zoomed-in view of greyscale image

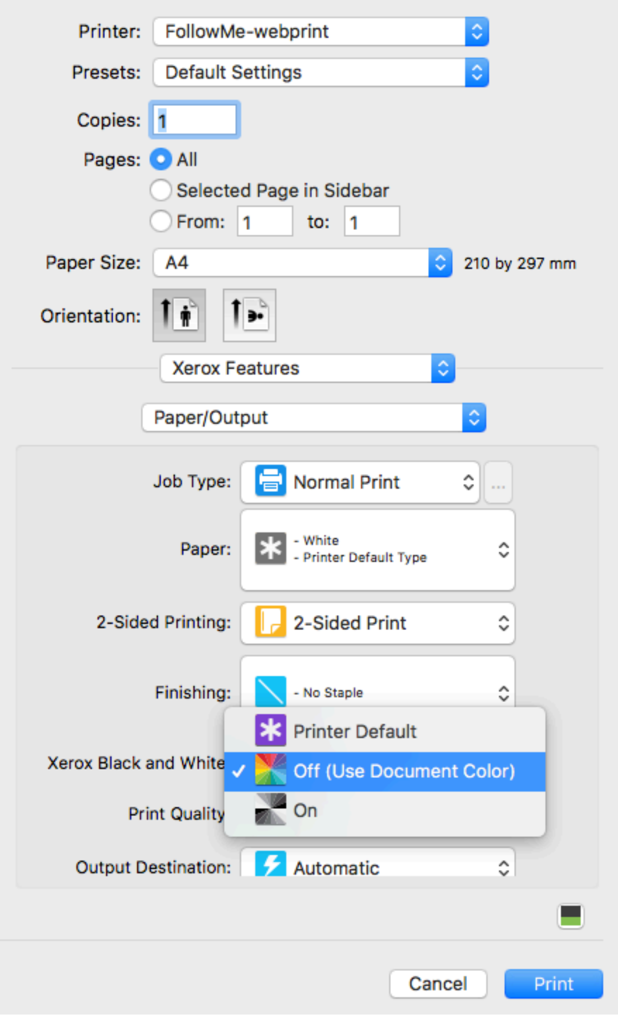
Figure 6.4 Line-based halftoning in material extrusion 3D printing

User interface

When analysing the user interfaces of printing software, it becomes apparent that these interfaces are, apart from transformation properties, often limited to selection fields and checkboxes, rather than numeric inputs. Moreover, the settings are more goal oriented. For example, rather than having to resize pages to fit multiple pages on a single sheet, the user is presented with easy options to automatically fit a number of pages on the sheet. Additionally, controls in the printer's settings are also linked to icons or figures that give direct feedback on how user settings will influence the qualities of the final print. Figure 6.5 presents a subset of these icons.

Implications for intent-based printing

It is hard to apply an approach similar to rendering intents because in 3D printing there is no baseline value to compare to. Moreover, the 2D printing approaches focus on parameters that are a more direct representation of the user's intent. These parameters are often controlled by categorical controls and checkboxes, rather than through numeric inputs often used for print settings in 3D printing. Finally, figures and on-screen simulations present feedback to users of the influence of their input.



Printer: FollowMe-webprint
Presets: Default Settings
Copies: 1
Pages: ● All
○ Selected Page in Sidebar
○ From: 1 to: 1
Paper Size: A4 210 by 297 mm
Paper: - White - Printer Default Type
Job Type: Normal Print
2-Sided Printing: 2-Sided Print
Finishing: - No Staple
Xerox Black and White: ✓ Off (Use Document Color)
Output Destination: Automatic

Figure 6.5 Printer interface in OS X. Icons visually present how the settings influence the printed result.

6.2
Intent facilitation

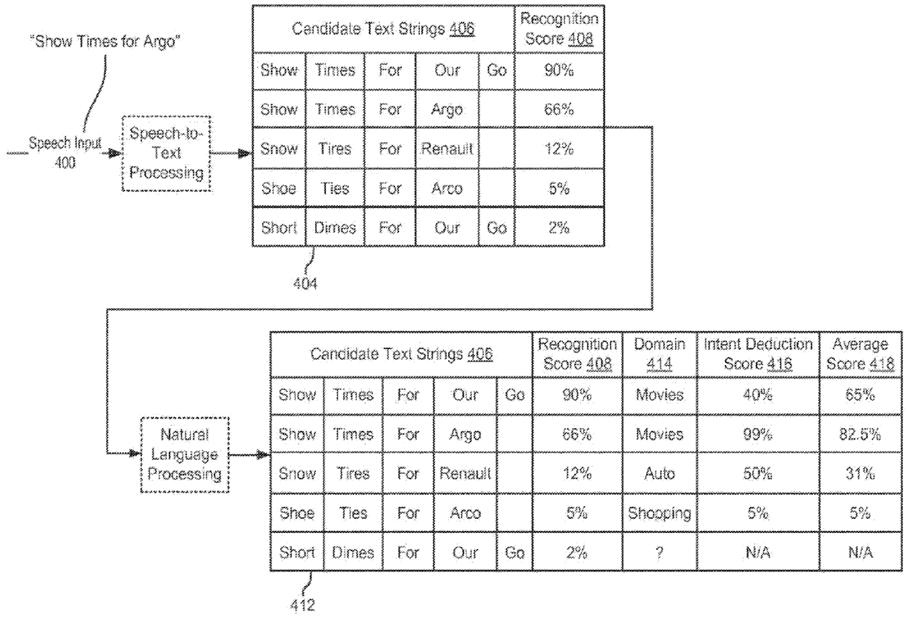
6.2.1. INTENT DEDUCTION

Providing a better user experience by measuring the intent of the user is applied in a variety of different contexts. In order to find out more about the techniques applied to derive user intent, a selection of patents on user intent recognition in different product contexts was analysed. This paragraph discusses the most notable intent deduction methods derived from these patents, which can serve as inspiration for intent-based 3DP approaches. These methods all share the same definition of intent as assumed in this report, since in all cases the intent of the user is translated into a set of actions that should be performed after intent deduction to accomplish the user's goals.

Intent in speech input

Apple Inc. has patented a method for identifying a user's intentions in order to facilitate better responses by their voice assistant (Figure 6.6) (Evermann, 2014). Common voice recognition works by interpreting audio signals and comparing these signals to known audio patterns associated with words. In order to determine the correct sentence from audio input, a natural language processor determines a set of candidate strings, which consist of different series of possible words derived from the input audio. Subsequently, it assigns each candidate string a score for how well that series of words matches the audio signal. However, by recognition based solely on individual words, the natural language processing can determine that even a sentence that does not make any sense matches the audio signal best. Therefore, additional methods are necessary to make sure that the best recognized text string makes sense.

In order to solve this problem, Apple Inc. applies a technique called intent deduction. Now, a series of words does not only earn a recognition score, but also an intent deduction score. The average of these scores determines the best matching candidate string. The intent deduction score works through a domain structure. Each word gets several domains attached to it. Based on the domains in which each word in the candidate strings exists, the intent deduction algorithm determines an intent deduction score. Figure 6.6 depicts how this intent deduction score can lead to a better interpretation of the audio signal, since the movie title "Argo" matches the domain "movies" and the words "Our" and "Go" do not.



Candidate Text Strings 406					Recognition Score 408
Show	Times	For	Our	Go	90%
Show	Times	For	Argo		66%
Snow	Tires	For	Renault		12%
Shoe	Ties	For	Arco		5%
Short	Dimes	For	Our	Go	2%

Candidate Text Strings 406					Recognition Score 408	Domain 414	Intent Deduction Score 416	Average Score 418
Show	Times	For	Our	Go	90%	Movies	40%	65%
Show	Times	For	Argo		66%	Movies	99%	82.5%
Snow	Tires	For	Renault		12%	Auto	50%	31%
Shoe	Ties	For	Arco		5%	Shopping	5%	5%
Short	Dimes	For	Our	Go	2%	?	N/A	N/A

Figure 6.6 Identifying a user's intentions from speech input (Evermann, 2014)

A similar implementation could be used in the prepare phase of material extrusion 3DP by linking certain setting changes to intent domains. For example, once the user changes print settings in ways that are commonly associated with a certain intent, the system could identify that the user is probably having an intent belonging to that specific domain.

Method and apparatus for deducting user intent and providing computer implemented services

Apple Inc. also patented a method to deduct user intent and provide relevant computer implemented services to the user (Luciw, Capps & Tesler, 1995). This method ties threshold values to certain action events (Figure 6.7). If an action, or set of actions, is measured, the system creates a new event and searches for related events in a pre-existing database. If the database has a valid intent hypothesis for the measured actions, the system prepares to execute additional actions to achieve the user's intended results, that only have to be confirmed by the user before execution.

A similar system could be applied in the preparation phase of 3DP by creating a database of patterns that can be linked to certain intents. These patterns could be related to print settings, material, printer configuration and model geometry. For example, once the system has an intent hypothesis, it could prompt the user in Cura asking whether the hypothesis is correct. When accepted, the system could optimize the print settings, model orientation and printer configuration towards meeting the user's intended result.

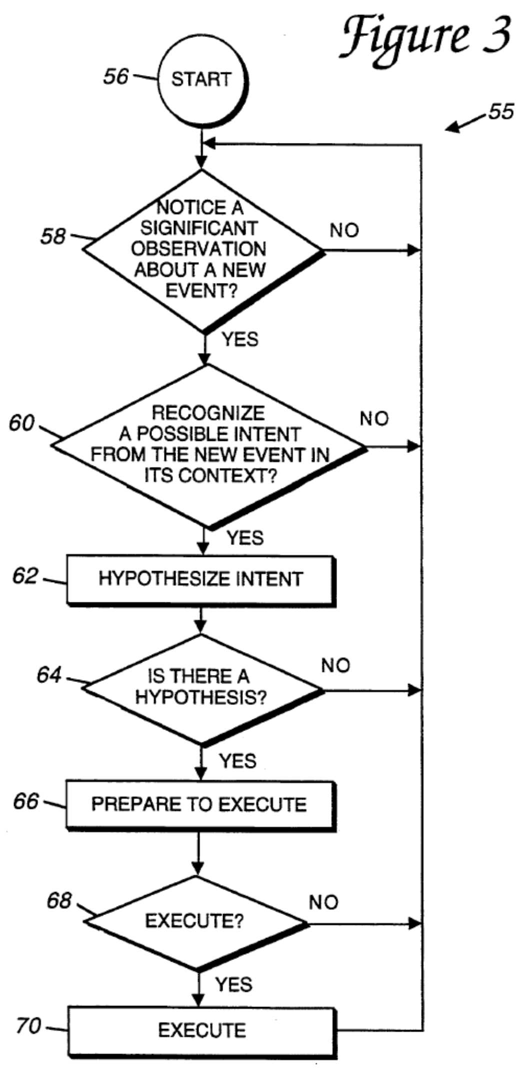


Figure 6.7 Detecting user intents and proposing to execute hypothesis (Luciw, Capps & Tesler, 1995)

Classifying the intent of user input

Microsoft (Lulz & Dietz, 2013) has patented an intent deduction algorithm for classifying user intent of user input for touchpads (Figure 6.8). A common issue when operating a laptop is that the user makes unintended contact with the touchpad causing an interruption of the currently performed task. Moreover, the user may interact with the touchpad in different manners, which are all connected to different actions in the operating system. In order to distinct between intended and unintended touches, and to determine the intentions of the user when interacting with the touchpad, the algorithm uses a combination of hierarchical threshold measurements.

The approach of intent deduction by Microsoft is similar to the previously discussed patent by Apple for triggering additional actions. An important difference is that Apple's system prompts the user for confirmation, whereas Microsoft's approach triggers automatic actions. Both can be applied to intent-based printing, but each have their distinct benefits. The benefit of Microsoft's approach is that the user does not have to constantly confirm actions, whereas Apple's approach ensures that the user stays informed at all times.

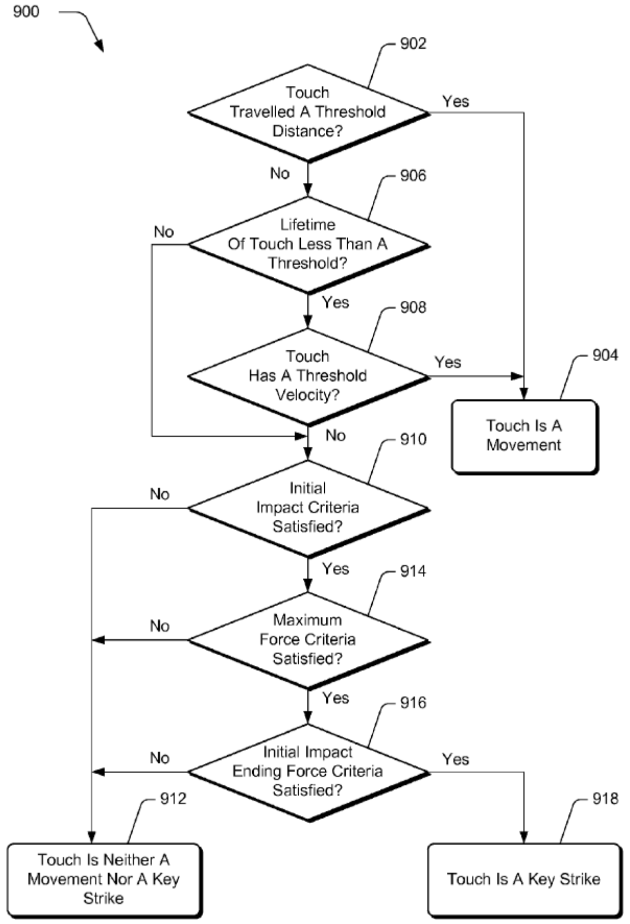


Figure 6.8 Classifying user intent from touch input (Lulz & Dietz, 2013)

6.2.2. INTENT FACILITATION

As mentioned in paragraph 5.2.2, knowledge of product configuration systems, or product configurators, can be used as an inspiration for intent-based 3D printing because product configurators are widely applied to translate customer requirements to custom product configurations.

According to Trentin et al. (2012) the fundamental functions of a product configurator are:

1. Communicating the company's product offerings to the consumer
2. Checking the completeness and validity of the description of the product variant that the customer is willing to buy and the company agrees to supply
3. Providing real-time information on price, cost, delivery terms, technical characteristics, etc. of the product variant
4. Making quotations
5. Generating the product data necessary to build the product variant requested by the customer

These fundamental functions are similar to the functions that slicing software should provide:

1. Communicate possible results that the Ultimaker printers can facilitate through purchasable print cores and filamens
2. Checking the completeness and validity of the resulting tool path
3. Providing real-time information on cost, print time, qualities of the resulting part, etc.
4. Suggesting more beneficial printer configurations and process parameters
5. Generating tool path information (GCODE file)

Mechanisms for improving product quality

In addition to the fundamental functions, Trentin et al. (2012) clarified five mechanisms through which the use of a product configurator may improve product quality:

1. Better match between the customer's idiosyncratic needs and the product solution delivered by the company
2. Less reliance on ad hoc solutions to fulfil customer needs
3. Reduction of product configuration errors
4. Increased focus of designers and process engineers on incremental and innovative improvements of the company's products and processes
5. Faster adoption of enhanced product and process solutions

While all five of these mechanisms could potentially improve intent-based 3D printing solutions, only the first three can be translated into three design goals to consider for designing intent-based 3D printing solutions:

- Better match user intents with the 3D printing products offered by Ultimaker
- Less reliance on solutions specific to single prints to fulfil intents
- Less 3D printed results that do not have the intended qualities

Design of product configuration systems

Most product configuration systems are centralized, i.e. the configuration is limited to a single company and its product family (Zheng, Xu, Yu & Lui, 2017). Therefore, Zheng et al. (2017) proposed a framework for decentralized product configuration through an open architecture product platform. The approach of Zheng et al. is beneficial because it allows third party vendors and suppliers to provide additional tools to the user in order to meet customer requirements. Because the conceptual framework for personalized product configuration proposed by Zheng et al. serves as good inspiration, some of it's enabling features are discussed.

A conceptual framework for personalized product configuration

The conceptual framework can be broadly separated into two parts: a technical configurator and a sale configurator. The technical configurator consists of the back-end processing and the sale configurator provides the user interaction on the front-end of the configurator.

The technical configurator enables modularity and scalability. The modular design aims to satisfy user preferences on a macro-level and the scalable on a micro-level.
The modular design offers three types of modules: common modules, customized modules, and personalized modules. Common modules can be applied to any product. Customized modules are add-on modules developed by third party vendors that support a variety of customized products. Finally, personalized modules are engineer-to-order add-on modules developed by customers and third party manufacturers specific to their design requirements.
The scalability of the design focuses on optimizing process parameters towards user preferences without violating constraints. This optimization is applied to a configuration consisting of previously defined modules.

Opportunities for intent-based printing

Designing an approach for intent-based printing can take inspiration from product configuration systems and how they translate user requirements into product configurations. Developing such an open system for intent-based print preparation would yield interesting capabilities for companies that deal with specific applications and intents. For example, through creating an open system, operators can be enabled to create print profiles aimed at specific user intents, which designers in the same context can apply to their designs. In such a scenario, Ultimaker could be in charge of developing common modules that aim to satisfy more broadly defined user intents and companies can create customized- and personalized modules applicable to parts with similar designs and highly specific parts respectively.

6.3
Conclusions

This paragraph presents the answers to the research questions posed at the beginning of this chapter:

What can be learned from intent-based 2D printing and from intent-facilitation in non-printing applications to improve intent-based 3D printing?

2D printing approaches focus more often on parameters that are a direct representation of the user's intent compared to 3D printing (goal-driven instead of process-driven). Moreover, parameters in 2D printing are often controlled by selection fields and checkboxes, rather than through numeric input. This makes the printing process more simplistic and lowers the chances of non-optimal setting combinations. Additionally, figures and screen simulations present direct feedback of the influences of user input, presenting the relationship between the adapted setting and the result.

Finally, rendering intents in 2D printing represent adaptations of baseline values, such as colour codes, extracted from the to-be printed file. However, in 3D printing, such baseline values are often not set during the create phase, nor communicated to the slicing software (apart from position). Therefore, in order to apply a similar approach as 2D printing, the communication of such information presents a challenge for intent-based 3D printing.

What can be learned from patents on user intent recognition in different product contexts to improve intent-based 3D printing?

- Designing an approach for intent-based printing can take inspiration from product configuration systems and how they translate user requirements into product configurations.
- Speech recognition technology by Apple Inc. shows that coupling user input (in this case print settings) to intent-domains could positively affect intent recognition and system performance.
- Systems that automatically act on deduced user intents can react manually or automatically. Manual reaction prompts the user for confirmation to ensure the user stays in control, whereas automatic reaction lowers the amount of required user actions to reach intended results.

7.
Intent

This chapter analyses the intents that exist for 3D printing use-cases. First, different intents are identified according to research by Wohler Associates and Ultimaker. Next these intents are used as an input for user testing to find out how users apply these intents in their 3DP workflow and whether intents can be described by simpler variables. Finally, the subject of learning based on user input is discussed. This chapter aims to answer the following questions:

- What variables can be used to describe user intents?
- What actions do users take to achieve their intended results?
- Can learning algorithms be applied to deduce intents based on actions performed by the user?

7.1
Intent

Wohlers Associates (2017) has conducted research on 3DP intents for all AM processes and found the intent distribution depicted in Figure 7.1:

Moreover, in a survey Wohlers Associates performed, they asked manufacturers which industries they serve and to give an indication of the approximate revenue in percentages from them. Figure 7.2 shows the results of this survey. While these numbers are impossible to relate to certain intents, they do show different fields of applications with possible unique intents and / or different intent distributions.

Ultimaker has also defined several 3DP intents, of which these are deemed the most important:
- Quickly choose a concept direction
- See how different components fit together
- Produce an end-use part
- Evaluate the look and feel
- Make an (aesthetic) presentation model
- Prove a mechanical principle to work
- Get a first understanding of shape and form
- Validate a final iteration before going into production or making a final part
- Print a tool to aid manufacturing or other processes during a project.
- Prepare for vascular surgeries
- Prepare for trauma surgeries
- Print an architecture massing
- Print an architecture presentation model

An important note is that while the intents from the research by Wohlers Associates are based on the entire AM market, Ultimaker's intents are based on FDM machine usage only. Consequently, the classification made by Wohlers Associates is slightly different from the classification by Ultimaker. However, both classifications cover similar applications. However, Wohlers Associates define separate classes for moulds for silicone- and metal casting, whereas in Ultimaker's definition, they would probably be considered tool aids.

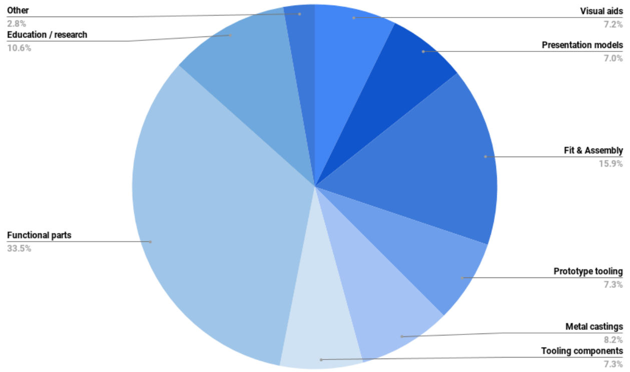


Figure 7.1 Intent distribution (Wohlers Associates, 2017)

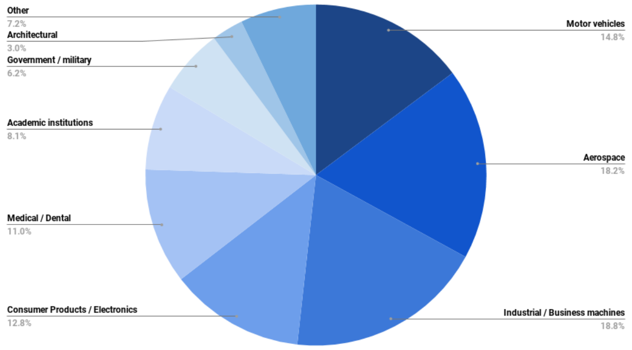


Figure 7.2 Approximate revenues (Wohlers Associates, 2017)

The last four intents identified by Ultimaker focus on specific application fields, namely medical and architectural. There are valid reasons to define separate intents for these applications, even though they might appear similar to the other, more broadly applicable intents. For example, the architectural presentation model might be a subset of the intent "make an (aesthetic) presentation model". However, the requirements for printing an architectural presentation model are often different from product presentation models. For architectural presentation models, there is an increased risk of losing important details due to the limited resolution of the material extrusion process, because architectural models are often scaled down versions of the real design.

Implications for intent-based printing
The example shows that two different intents, while both related to 'making a presentation model' can be very different in application. Therefore, an important note to make when presenting users with broad intents is that they might interpret them differently; an architect envisions a different set of actions when making a presentation model than a product designer.

7.2
Explorative research

In order to gain first insights into how users go about realising their intended results during the 3DP workflow, an explorative research was conducted. The aim of this explorative study is to:

- Understand what actions users take to achieve intended results during the different phases of the 3DP workflow
- Understand how much users take the intended result into consideration during the different phases of the 3DP workflow
- Get an understanding of how users apply multiple intents in a project context

This paragraph describes how the research was conducted and the results of the study.

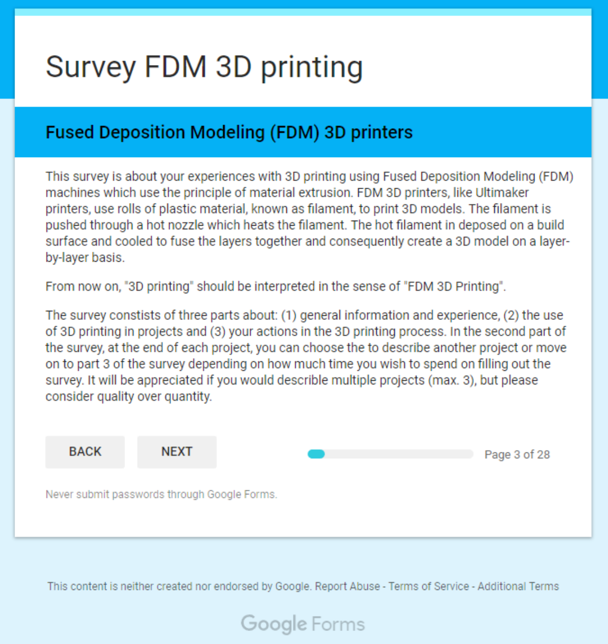
Subjects
A total of 7 Industrial Design students at the Delft University of Technology participated in study. 85.7% of the subjects were males (N = 6) and 14.3% were females (N = 1), ranging in age from 22 to 27 years old. The average age of the subjects was 24.3 years. People with no experience with FDM 3DP were not accepted to the study.

Procedure
Subjects were asked to fill out a 15-to-30-minute survey (Figure 7.3) about 3D prints they recently made. The amount of time since the 3D printing took place was recorded, as well as a score for remembrance of the 3DP activity in order to asses possible intervening variables.

Their intentions for multiple prints during multiple projects (N = 13) where recorded. Additionally, they were asked what qualities they deemed important for prints during the projects. Finally, they were asked questions about how much they took the intended results into consideration during the different phases during the 3DP workflow.

Since subjects were industrial design students, the list of user intents determined by Ultimaker, as discussed in paragraph 7.1, was adapted. Intents related to medical procedures and architectural design were eliminated from the list since they are not applicable to industrial design.

Figure 7.3 Survey for explorative research



Survey FDM 3D printing

Fused Deposition Modeling (FDM) 3D printers

This survey is about your experiences with 3D printing using Fused Deposition Modeling (FDM) machines which use the principle of material extrusion. FDM 3D printers, like Ultimaker printers, use rolls of plastic material, known as filament, to print 3D models. The filament is pushed through a hot nozzle which heats the filament. The hot filament in deposed on a build surface and cooled to fuse the layers together and consequently create a 3D model on a layer-by-layer basis.

From now on, "3D printing" should be interpreted in the sense of "FDM 3D Printing".

The survey constists of three parts about: (1) general information and experience, (2) the use of 3D printing in projects and (3) your actions in the 3D printing process. In the second part of the survey, at the end of each project, you can choose the to describe another project or move on to part 3 of the survey depending on how much time you wish to spend on filling out the survey. It will be appreciated if you would describe multiple projects (max. 3), but please consider quality over quantity.

Never submit passwords through Google Forms.

This content is neither created nor endorsed by Google. Report Abuse - Terms of Service - Additional Terms

7.2.1. QUANTITATIVE RESULTS

Since even significant correlations ($p < 0.05$) are susceptible to change due to the low number of participants, only the results with a significance of $p < 0.01$ are presented:

Correlations between different intents during the project

1. There is a strong positive relationship between getting a first understanding of shape & form and seeing how different components fit together ($r = 0.732$, $p < 0.01$).
2. There is a strong positive relationship between getting a first understanding of shape & form and evaluating the look and feel ($r = 0.690$, $p < 0.01$).
3. There is a strong positive relationship between getting a first understanding of shape & form and making an (aesthetic) presentation model ($r = 0.690$, $p < 0.01$).
4. There is a strong positive relationship between proving a mechanical principle to work and evaluating the look and feel ($r = 0.732$, $p < 0.01$).
5. There is a strong positive relationship between seeing how different components fit together and evaluating the look and feel ($r = 0.732$, $p < 0.01$).
6. There is a strong positive relationship between evaluating the look & feel and making a presentation model ($r = 0.732$, $p < 0.01$).

Correlations between different intents and important qualities

There is a strong positive relationship between making a presentation model and the importance of aesthetics ($r = 0.751$, $p < 0.01$).

Correlations between important qualities of 3D prints during the project

There is a strong positive relationship between the importance of print speed and the importance of ease of printing ($r = 0.797$, $p < 0.01$).

Correlations between importance of print qualities and process

There is a strong negative relationship between the importance of post-processing and the consideration of important qualities during the printing phase ($r = -0.738$, $p < 0.01$).

Discussion of quantitative results

The quantitative results of this explorative research indicate several correlations between print settings, user intent, and part qualities. Even though results are significant, the results should only be used as indicators because of the low amount of test subjects.

Discussion of correlations between different intents during the project

A problem in interpreting the correlations between intents is the fact that it is an unknown whether the intents listed by the participants were realized by making a single print or multiple prints. However, some interesting conclusions can be drawn from the results.

First, correlations 3 and 6 show that industrial design students often make at least one aesthetic prototype during a project before making a final presentation model. Therefore, it is likely that the chances of a user's intent being 'making an (aesthetic) presentation model' increase if at least one aesthetic prototype has been made. This suggests that project history could be a useful variable in determining future intents.
Second, correlations 2, 3, and 6 suggest that the list of intents established by Ultimaker can be clustered (possibly depending on the application field). In the field of industrial design, the intents 'get a first understanding of shape and form', 'evaluate the look and feel' and 'make an (aesthetic) presentation model' seem to belong to a cluster with aesthetics as common denominator.
Additionally, correlations 1 and 5 show that for industrial design students, how components fit together is also an important contributor to the aesthetics of the product.
Finally, correlation 4 suggests that both intents related to aesthetics and intents related to functionality are often pursued within a single project in the industrial design field.

Discussion of correlations between different intents and important qualities during a project

The resulting relationship between the intent of making a presentation model and the important of aesthetics seems very logical (even if it is unknown whether the relationship exists within a single print or between multiple prints), since aesthetics is one of the most important properties of presentation models.

Discussion of remaining correlations

The correlations between different print qualities and correlations between print qualities and process parameters are not taken into consideration, since it is unknown whether these relationships exist between or within different instances of the 3DP workflow during a project.

7.2.2. QUALITATIVE RESULTS

Analysing participants' answers to open questions in the survey has led to qualitative results that are discussed in this section:

Changes made to the model in order to facilitate material extrusion printing

Users reported the following changes to the model during the create- and prepare stages to achieve improved printability:

Actions during the create phase:

- Cutting the model into pieces. The model is cut into pieces for reasons like (1) faster printing and (2) fitting components on the build plate or (3) to just print part of the model that should be tested.
- Manually adding supporting structure to the model.
- Adding chamfers: Chamfers are added to avoid elephant feet at the bottom of the model, because else the model will be wider at the bottom and therefore not be dimensionally accurate or look terrible.
- Adding fillets: Fillets were added by a participant to save material and to improve the print process, as the participant believes it enables faster printing and avoids vibrations due to otherwise required accelerations at sharp corners. Avoiding vibrations also positively affects the print quality.
- Removing model features: Some features in the model, such as thin walls and large overhangs, were deleted from the model since they were expected to be unprintable.
- Changing the orientation of features of the model: The participant changed the orientation of the holes, because else the hole would be printed using overhangs.
- Change the wall thickness of the model: The wall thickness is increased for models that are 3D printed in order to have similar strength as injection moulded parts with thinner walls.
- Create bigger tolerances to make sure components fit together.

Actions during the prepare phase:

- Scaling the model to fit to the build volume.
- Changing the orientation of the model: Changing the orientation is listed for several reasons: (1) to improve the part strength, because the part is stronger in the direction of the print lines, (2) to improve the aesthetics, because the bottom surface is the smoothest looking surface when printing on a glass build plate

Changes made to the model for post-processing purposes
Changes made for post processing were related to part orientation in order to avoid support material altogether, or at least on the visible sides of the part. Or to deliberately orientate a flat visible surface to contact the build surface, since this creates a smooth layer.

Exporting the model to a tessellated geometry file (STL, OBJ, 3MF)
Participants did not take file format into consideration but did check the quality of tessellated geometry (amount of triangles in the mesh). A number of participants chose the maximum amount of triangles by default to ensure high mesh resolution, as they supposed it did not significantly influence processing time.

Discussion of qualitative results
Changes made to the model in order to facilitate better 3D printing
Analysis of the changes made to the model suggests that users are (sometimes) willing to adapt the model to facilitate better printing. Moreover, users were able to express the purpose behind the changes they made. A number of participants were also familiar with the influence of model orientation on part strength and aesthetics.

Changes made to the model for post-processing purposes
Reported changes made to the model for post-processing purposes were mostly limited to the avoidance of support material. However, taking advantage of the smooth bottom surface of the 3D print due to the glass build plate is an interesting use of affordances to achieve intended qualities.

Exporting the model to a tessellated geometry file (STL, OBJ, 3MF)
Most users do not consider the file format they use to export the tessellated geometry, and therefore do not take advantage of the affordances that these file formats present. Therefore, there is an opportunity to make better use of the (unique) affordances offered by different file formats.

7.2.3. CONCLUSIONS
These are the most important findings of the explorative research:

- Project history might be an important factor in determining a user's intent.
- There appears to be an opportunity for clustering the intents listed by Ultimaker dependent on field of application.
- Intents related to both part functionality and aesthetics can appear in a single project context.
- For industrial design students, component fit is important for aesthetics.
- There is an opportunity to take advantage of the unique functions of different file formats for intent-based printing, since most users do not use these by default.
- Changes made to the model for post-processing were not only focussed towards minimizing support material, but also to make effective use of the aesthetic properties of the first layer.
- Apart from part-separation, some users are willing to make small adaptations to their models to improve printability.

7.3
User study

The intents identified by Ultimaker and the intents that are distinguished in the Wohler's Report are similar. This study conducted with 22 industrial design students aims to identify the distribution of 3DP intents for material extrusion 3D printers in a product design context.

Subjects
A total of 20 Industrial Design students at the Delft University of Technology participated in the pilot experiment. 60% of the subjects were males (n=12) and 40% were females (n=8), ranging in age from 18 to 27 years old. The average age of the subjects was 23.5 years. People with no experience with FDM 3DP were not accepted to the test.

Materials
Participants were asked to fill out an online survey made with Google Forms about the preparation of 3D prints for an FDM printer. Since subjects were industrial design students, the list of user intents determined by PM was adapted; intents related to medical procedures and architectural design were eliminated from the initial listing of user intents.

Parts were prepared for Ultimaker 2(+) printers or similar desktop FDM 3D printers using various versions of the Cura slicing software. Personal computers owned by the participants were used to access the online survey.

Procedure
Subjects were asked to fill out a 3-to-5-minute online survey about 3D prints they recently made. The amount of time since the 3D printing took place was recorded, as well as a score for remembrance of the 3DP activity in order to assess possible intervening variables.

Results
The results of the study show that a 3DP intent that is not considered in the study is to print objects for fun. The results of the study are visualized in the Venn diagram in Figure 7.4.

When observing the relationships between the different intents displayed in the Venn diagram, a directional relationship seems to exist. Intentions related to functional parts, both in process and in part behaviour, seem to be located on the left of the diagram, whereas intentions related to aesthetics seem to be located on the opposite side. Moreover, intentions that are often performed in the early stages of a project seem to be located on the top of the diagram, whereas intentions related to the latter stages of a project are located at the bottom.

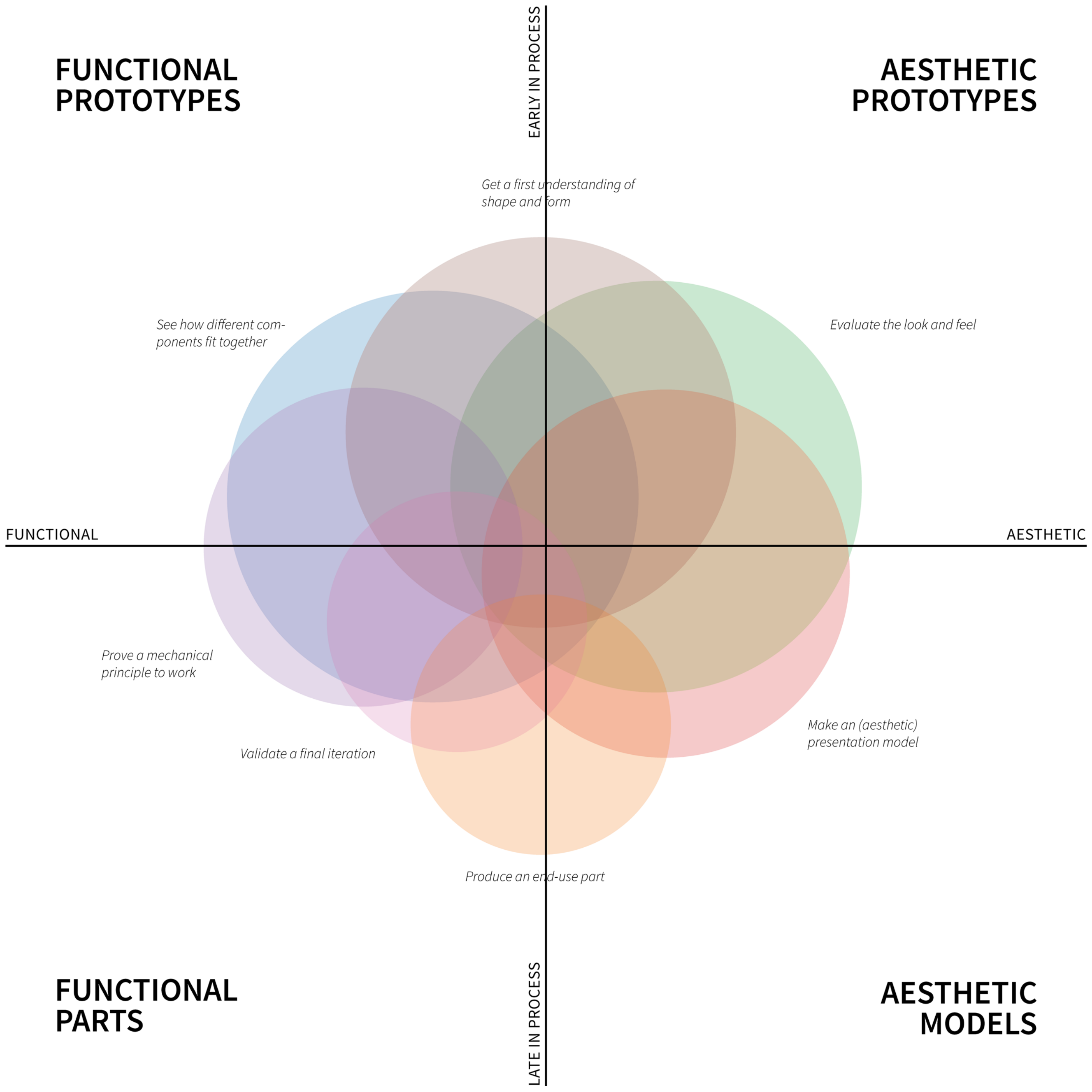


Figure 7.4 Venn chart of user intentions in product development context (N=20). The size of the circles indicates the amount of participants who had this intent. The circle overlaps show the amount of participants that had multiple intents for a single print.

Principal Components Analysis

In order to test the assumed existence of functional-aesthetic and prototype-final product axes, a principal component analysis (PCA) was conducted on the measured user intentions. The intentions ‘quickly choose a concept direction’ and ‘make a tool to aid manufacturing’ were excluded from the PCA since these intentions were considered outliers due to their low frequency in the dataset (N =1).

The first three principal components (PCs) accounted for 72.7% of the total variance. Since the first three PCs explain a high percentage of the total variance, the results and discussion will focus on them. The component loadings are listed in Table 7.1.

The intentions ‘prove a mechanical principle to work’ and ‘see how different components fit together’ exhibit high positive values for PC1, whereas ‘make an (aesthetic) presentation model’ and ‘evaluate look and feel’ exhibit negative values for PC1.

The intentions ‘see how different components fit together’ and ‘evaluate look and feel’ exhibit positive values for PC2, combined with a highly positive value for ‘getting a first understanding of shape and form’. In contrast, ‘produce an end-use part’ exhibits negative values for PC2.

The intents ‘produce an end-use part’ and ‘validate a final iteration’ exhibit positive values for PC3, whereas ‘make an (aesthetic) presentation model’ and ‘evaluate look and feel’ exhibit negative values for PC3. On the PC1-PC3 plane (Figure 7.5), three clusters of intents can be distinguished:

1. ‘Make an (aesthetic) presentation model’ and ‘evaluate look and feel’
2. ‘Prove a mechanical principle to work’ and ‘see how different components fit together’
3. ‘Get a first understanding of shape and form’, ‘produce an end-use part’ and ‘validate a final iteration before moving into production’.

Discussion

Principal components analysis is normally applied to scale variables, but in this case PCA is applied to boolean values (either 0 or 1). In order to lead to valid results using boolean values, the PCA at least requires more data points to account for the larger errors in boolean data compared to scale data (the minimum difference between values in boolean data is 100%, whereas for Likert scales from 1 to 7 this is already lowered to 16.7%). However, even when applied to large datasets, the use of PCA on binary data is still debatable and its results should only be considered as indications. The component scores should therefore not be considered as actual values, but as indications. Since the results of the PCA appear similar to what the Venn diagram indicates, it’s likely that the derived principal components are indeed useful for describing user intents. The three clusters appear to be distinguished by importance of aesthetics, functionality and process, which confirms the assumed directionality seen in the Venn diagram.

Conclusions

- Intents can indeed be further clustered depending on field of application (as was suggested from explorative results)
- Intents in industrial design applications appear to be distinguished by importance of aesthetics, functionality and process

Intents	PC1	PC2	PC3
See how different components fit together	.866	.311	.099
Produce an end-use part	-.153	-.748	.312
Evaluate the look and feel	.422	.413	-.521
Make an (aesthetic) presentation model	-.250	.006	-.675
Prove a mechanical principle to work	.908	-.088	.123
Get a first understanding of shape and form	-.011	.909	.156
Validate a final iteration before going into production	.048	.029	.844

Table 7.1 Component loadings

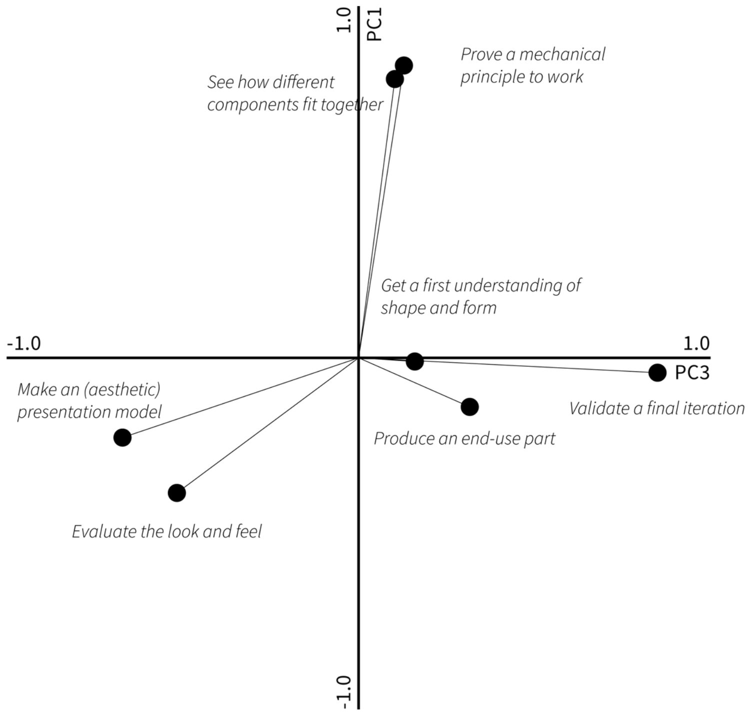


Figure 7.5 PC1-PC3 plane

7.4

Predicting user intent

In addition to gaining insights in the intents of user, data from both user studies was analysed in an effort to relate print settings with user intents. However, in both cases, the dataset proved far too little to find any significant relationships. If such relationships could be found, the input of users could be used to derive their intended end result, and subsequently, the slicing software could attempt to correct the user. Alternatively, slicing software could prompt the user with hypothesized further actions or perform them automatically like the earlier discussed patents (Paragraph 6.2).

Because these relationships could not be derived from user research, the information gathered by the slicer was analysed. However, the slicing data recorded by Ultimaker only gathers a subset of the available settings offered in the interface. Moreover, it does not record information about user intent, making it impossible to derive a correlation between intents and print settings. Additionally, model geometry, which is assumed to have an influence on intent, is reduces to only the model's bounding box dimensions due to privacy. Therefore, applying learning algorithms to data of sliced data does not seem feasible. Even if applying learning algorithms would turn out to be feasible in the future due to improved data input, it would go beyond the scope of this thesis.

7.5
Conclusions

This paragraph presents the answers to the research questions posed at the beginning of this chapter:

What variables can be used to describe user intents?

- Intents can be clustered depending on field of application. As a result of this clustering, intents in industrial design applications appear to be distinguished by importance of aesthetics, functionality and process
- The process variable may include project history, which is suggested to be an important factor in determining a user's intent.

What actions do users take to achieve their intended results?

- Users do not take advantage of the unique functions of different file formats for intent-based printing since most users do not use these by default.
- Changes made to the model for post-processing were not only focussed towards minimizing support material, but also to make effective use of the aesthetic properties of the first layer.
- Apart from part-separation, some users are willing to make small adaptations to their models to improve printability.

Can learning algorithms be applied to deduce intents based on actions performed by the user?

It is difficult to implement learning algorithms in intent-based 3D printing approaches. Current slicing data from Cura contains little information about the object geometry, and no information about user intent, that could be used to relate print settings to certain intended results. Moreover, applying such learning algorithms assumes that the user purposefully changes print settings based on intent. Users with little knowledge about 3D printing could introduce errors in the learned relationships.

8.
Vision

This chapter transforms earlier identified opportunities for intent-based 3D printing into eight design opportunities. Based on these opportunities a design vision and design criteria for intent-based 3D printing are established.

8.1
Design opportunities

Several limitations to the current 3D printing workflow and opportunities for the design of intent-based 3DP approaches were identified during the analysis phase of this project. This paragraph summarises these opportunities and classifies them to form design opportunities (D1-8) that serve as an input for later ideation. These design opportunities are described below with the limitations to the conventional 3D printing workflow and the opportunities for intent-based 3D printing that they are based upon.

D1: Goal-oriented print preparation

Goal-oriented print preparation differs from the conventional process-oriented print preparation by focussing on controlling resulting part qualities, rather than process parameters.

D1 is based upon:
- There are no clear incentives presented to change print settings
- It is not completely understood how the process parameters influence the final part properties
- Communication of limitations to post-processing by nozzle- and material selection

D2: Reducing the knowledge threshold

Reducing the knowledge threshold aims to lower the amount of required process knowledge for 3D printing by lowering the knowledge requirements throughout the 3D printing workflow and guide users towards optimal solutions

D2 is based upon:
- Continuous scale settings assume that users have the required process-knowledge to control the print setting
- The combined effect of changing multiple process parameters is hard to determine
- Advanced controls such as per model settings and powerful experimental features are hard to find
- Categorical parameter control simplifies the preparation process and lowers the chances of non-optimal parameter combinations

D3: Component-level control

Component-level control enables users to control their model in facets, or components. These components can be configured to be printed using different process parameters to enable part structures with different qualities compared to the rest of the model.

D3 is based upon:
- By leveraging the properties of the material extrusion process, material can be deposed in patterns to create structures (or parts of the printed model) with specific dynamic behaviour
- Product customization drives the need for component level-control over the model during print preparation

D4: Promotion of 3D printing affordances

The promotion of 3D printing affordances aims to familiarise users with the unique possibilities offered by the material extrusion process to ensure that users pick an optimal solution from a broader solution space.

D4 is based upon:
- Users do not take as much advantage as possible of different materials and nozzle sizes
- Some surface textures and features that are hard to model in CAD software can be created though the modification of existing tool path information and the addition of extra tool path information.

D5: Management of 3D printers

The management of 3D printers aims to ensure that users are able to optimally achieve intended results in scenarios with multiple users and / or multiple printers, without ruining each others user experience. Optimal planning of machine configurations, material & nozzle supply, maintenance and real-time information of the impact of machine availability during print preparation are part of this management.

D5 is based upon:
- In scenarios with multiple users, individual users can ruin the plans of others by changing the printer configuration or printing for excessively long times
- In scenarios with multiple printers, it is not clearly communicated which printer configuration will lead to the fastest realisation of the part, since not only print time, but also configuration and material availability play a role in realisation time
- Users are informed about the print time, but this print time does not take delays for printer (planned) maintenance (by operators) into account
- Flexible- material and configuration techniques likely to be implemented in future 3D printers should be considered when designing intent-based approaches.

D6: User education

User education is about presenting educative experiences to users throughout the 3D printing workflow that help them increase their process knowledge and enable them to use material extrusion technology more effectively.

D6 is based upon:
- Process experience is not shared between operator and designer
- Educative experiences (such as unboxing) are not available to every user resulting in unawareness of affordances
- ‘Experts’ are over-confident and unintentionally ruin their prints by modifying print settings that have negative effects on print quality
- Users are willing to separate models into multiple models and make small alterations in order to improve printability

D7: Intent communication

Intent communication is about quantitative communication of user intentions between the create and prepare phases and between different users. Using this information, users are able to prepare the print more efficiently to achieve the desired result.

D7 is based upon:
- The operator does not know the user intent for the to-be-printed model
- The operator has no standardised method to influence how designers prepare their parts or to advise them
- Communication of desired properties of components of the realized part can enable intent-facilitation as found in 2D printing.
- Users do not take advantage of the unique functions of different file formats to communicate information between the create and prepare phases
- Intents in industrial design applications can broadly be described by the aesthetic, functional and process scales.
- Clustering of intentions may be specific to fields of application or companies & institutions.

D8: Feedback

Feedback covers the inclusion and (direct) representation of metrics that quantify how well the print is expected to meet, or meets the intended part qualities set by the user.

D8 is based upon:
- During the print phase, users get direct feedback of the effect of their adjustments, whereas during the prepare phase, users do not receive this direct feedback.
- Direct feedback during the print phase may be limited due to the use of more closed-off, closed-loop 3D printers.

8.2
Design vision

Currently, the 3D printing workflow is process driven: once the user decides to use 3D printing, the actions that are taken towards realizing the part are about manipulating the process, rather than manipulating properties of the resulting part. This paragraph describes the envisioned target experience for intent-based 3D printing.

Target experience

For intent based printing, the model should be central to the user experience. Intent-based printing should return to the essence of the process, to help realize a part with certain properties in the physical world according to a digital geometry. Therefore, process parameters, printer configuration and material should work together to facilitate this realization. They should be the result of the required actions for meeting the user's intended part qualities, rather than the starting point, because selecting the nozzle type and material before printing limits the possible solutions from the offset
.

Currently, one of the primary decisions that is made early in the preparation process is the selection of nozzle size and material. Consequently, various filters limit the configurable options of the user (Figure 8.1). In contrast, intent-based printing should postpone the filtration process as long as possible. Instead of acting as an input, configurations are an output of the system as a result of the the user's goals (Figure 8.2). Based on the wishes and requirements of the user, the intent-based preparation process should result in several configuration options, which can be supported, afforded or installed. Supported configurations are all possible configurations that are supported by the printer and meet the user's requirements. Afforded configurations are a subset of the supported configurations, with the additional requirement that they are available in the environment, i.e. the user has the required materials and print cores for the job and the printer is available for use. Once an afforded configuration is installed in a 3D printer, it is also an installed configuration.

Apart from leaving options open, the filtering process of going from supported- to afforded configurations could enable Ultimaker to present clear value propositions to their customers for using different print cores and materials. These value propositions would benefit both Ultimaker through selling more materials and nozzles and the customer through achieving intended results more effectively.

Additional to postponing the filtratration of available options as much as possible, intent-based printing should strive to:

- Reduce the knowledge threshold
- Promote the usage of affordances
- Introduce component-level control of the model
- Educate users
- Manage print clusters according to intents
- Introduce intent communication between the create and prepare phases
- Validate whether the intent of the user has been met

In short, the vision for intent-based printing is:

> 'IMPROVING THE 3D PRINTING WORKFLOW BY PROVIDING AN INTENT-BASED AND MODEL-BASED 3D PRINTING APPROACH THROUGH THE DELIVERY OF RESULT-DRIVEN OPTIONS, COMPONENT-LEVEL CONTROL AND INCENTIVES.'

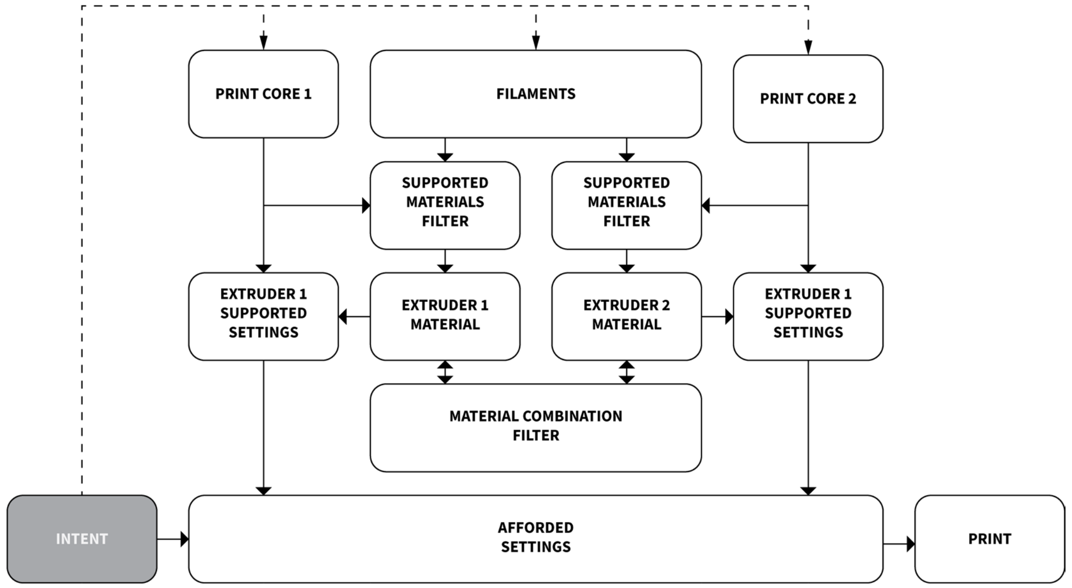


Figure 8.1 How nozzle- and material selection limits afforded process parameters in current print preparation

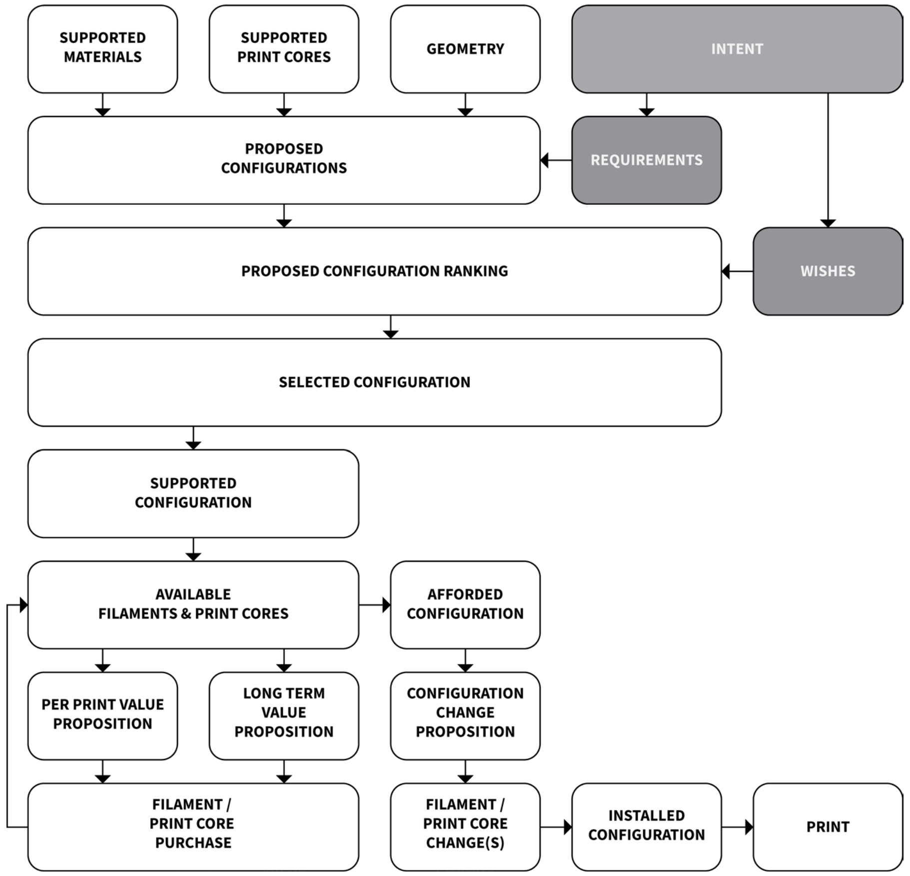


Figure 8.2 Nozzle and material as output of the print preparation process

8.3
Design criteria

This paragraph presents the design criteria that are used to evaluate the concepts to choose a final concept. These design criteria are wishes and requirements: wishes are beneficial to adhere to, and requirements must be met. In the next chapter, these wishes and requirements are used to evaluate the possible solutions and select the best solution.

Wishes

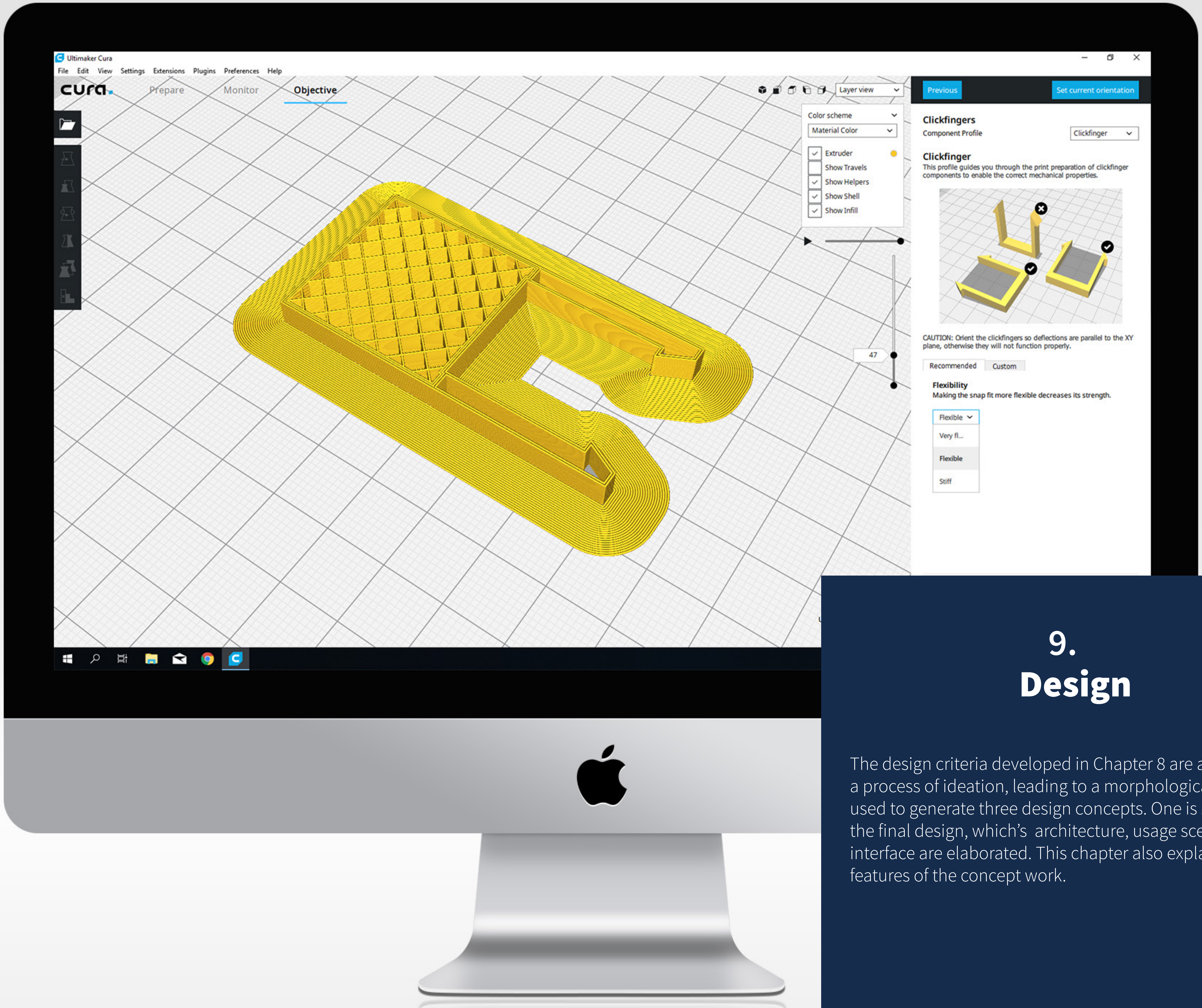
During the analysis phase, several needs of both the user and Ultimaker are identified that can positively contribute to the success of intent-based 3D printing solutions. These needs are translated into wishes for the concept, that are listed below:

- **Low-cost** It would be beneficial if the solution is low-cost.
- **Guidance** It would be beneficial if the user is guided towards ideal process parameters, printer configurations and material selection.
- **Future-proof** It would be beneficial if the solution is future proof and works (partly) with future products.
- **Satisfaction of highly specific intents** It would be beneficial if the solution is able to satisfy highly specific user intents.
- **Flexibility** It would be beneficial if the solution is applicable to a wide range of 3D printer hardware and printed models.
- **Feeling of control** It would be beneficial If the user feels in control of the outcome.
- **Educative** It would be beneficial if both beginning and advanced users are educated in 3D printing.
- **Feedback** It would be beneficial to have direct feedback on the influence of user input on part qualities.
- **Operator control** It would be beneficial for operators to have a means to control how others prepare 3D prints.
- **Advanced affordances** It would be beneficial if the solution can leverage the power of advanced affordances such as meta material structures to create dynamic model behaviour and tool path modifications to create advanced aesthetics.
- **Promotion** It would be beneficial if the solution presents clear value propositions to improve the quality and production process of 3D printed parts.
- **Printer Management** It would be beneficial if the management of printer clusters takes user intent into consideration when planning print jobs and printer configurations.

Requirements

As mentioned, the designed solution must also adhere to requirements in order to be able to implement the solution in Ultimaker's product family. The requirements used to limit the solutions found through ideation in the next chapter are listed below:

- **Repeatability** The solution must produce consistent resulting part qualities based on user intent.
- **Accessibility** The solution must be usable for beginning 3D printing users.
- **Functionality** The solution must facilitate 3D printing through converting user intents into process parameters, printer configurations and material selection to create 3D printed objects with desired part qualities.
- **Form, colour and finishing** The solution must adhere to the Ultimaker brand identity
- **Machine support** The solution must be applicable to material extrusion 3D printers developed by Ultimaker
- **Safety** The solution must at all times be safe for the users interacting with it.
- **Privacy** The solution must not require private data collection on an individual user basis on an Ultimaker controlled server.
- **Reliability** The solution must be trustworthy in terms of functionality, output quality and process time.
- **Installation** If the solution is an add-on product, users must be able to install the solution individually.
- **Maintenance** Users must be able to calibrate and execute small maintenance of the solution on site.
- **Feasibility** The solution must be feasible for introduction in the Ultimaker product family within 5 years.
- **Lifetime** The solution must not limit the lifespan of the Ultimaker printers that it is implemented in or cooperates with.



Clickfingers

Component Profile: Clickfinger

Clickfinger

This profile guides you through the print preparation of clickfinger components to enable the correct mechanical properties.

CAUTION: Orient the clickfingers so deflections are parallel to the XY plane, otherwise they will not function properly.

Flexibility

Making the snap fit more flexible decreases its strength.

Flexible

9.
Design

The design criteria developed in Chapter 8 are applied in a process of ideation, leading to a morphological chart used to generate three design concepts. One is selected for the final design, which's architecture, usage scenario and interface are elaborated. This chapter also explains how key-features of the concept work.

9.1

Ideation

Ideation was performed using several methods from the Delft Design Guide: How-Tos, Analogies & Metaphors, Brainwriting and Brain Drawing (Van Boeijen et al., 2003). The How-Tos method was used to generate multiple How-To questions per design opportunity that served as an input for the Brainwriting and Brain Drawing methods. These questions are listed in Table 9.1. Some of these questions contain analogies or metaphors for the experiences found in the 3D printing process.

Brainwriting and Brain Drawing

Both Brainwriting and Brain Drawing were used for idea generation through simultaneously writing down and drawing ideas on paper (Figure 9.1). This idea generation was based around the defined How-To questions.

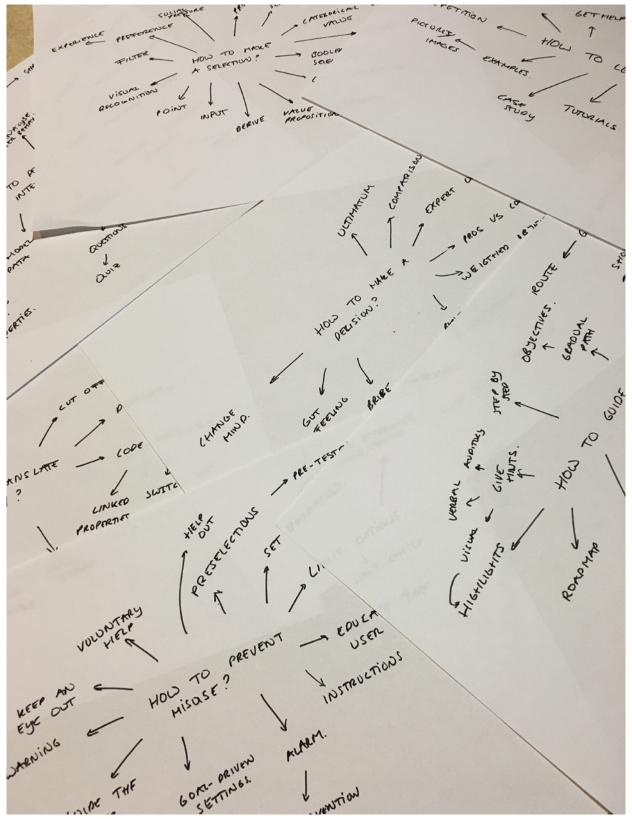


Figure 9.1 Brainstorming

Morphological chart

A Function Analysis was conducted that analyses what tasks the design needs to perform in order to achieve the desired experience as described by the design opportunities. This results in the following main-function and sub-functions:

Main function

Preparing prints through converting user intents into process parameters, printer configurations and material selection

Sub-functions

- **Import geometry** This sub-function describes how the to-be-printed model is transferred between the create and prepare phases.
- **Derive user intent** This sub-function describes how the user intent is measured.
- **Translate user intent** This sub-function describes how the user intent is translated into process parameters.
- **Guide the user** This sub-function describes how the user is guided towards the intended outcome.
- **Generate process parameter values** This sub-function describes how process parameter values are generated.
- **Present feedback** This sub-function describes how feedback is presented to the user about the resulting print-qualities.
- **Lower required process knowledge** This sub-function describes how the amount of required process knowledge is lowered to enable a wider user group to successfully prepare prints.
- **Educate the user** This sub-function describes how the user is educated about the affordances of material extrusion 3D printing.
- **Manage print jobs** This sub-function describes how print jobs are managed on available 3D printing hardware.
- **Ensure output quality** This sub-function describes how the qualities of the 3D printed part are ensured
- **Install configurations** This sub-function describes how the user is informed about the installation of required nozzles and materials.

The sub-functions are used to group the most promising ideas generated during the ideation phase, resulting in a Morphological Chart (Van Boeijen et al., 2003). This Morphological Chart, displayed in Table 9.2, is used to generate concepts in the next paragraph.

D1: Goal-oriented print preparation	**D2: Reducing the knowledge threshold**
How to filter goals based on user intent? How to define goal-driven controls? How to determine specific goals for fields of application and contexts? How to communicate limitations to post-processing? How to present post-processing possibilities?	How to put numbers into perspective? How to speak the user's language? How to measure user knowledge? How to simplify complex information? How to eliminate process knowledge requirements?
D3: Component-level control	**D4: Promotion of 3D printing affordances**
How to split models into components? How to prioritise components? How to solve counteracting component configurations? How to select individual components for configuration? How to orientate individual components?	How to advertise features? How to present value to consumers? How to present benefits of hardware and materials? How to communicate surface modification features during model creation?
D5: Management of 3D printers	**D6: User education**
How to communicate required printer configurations to users? How to manage printer configurations based on user requirements? How to consider user intent in print job planning? How to consider print job planning during intent-based print preparation? How to avoid users ruining each others plans?	How to gain new knowledge? How to present educative experiences? How to train users? How to share experience between users? How to present educative experiences throughout the 3DP workflow? How to educate users in design for material extrusion?
D7: Intent communication	**D8: Feedback**
How to translate intents into print parameters? How to communicate user intent between people? How to communicate user intent between the create and prepare phases? How to quantify user intents for communication? How to take field of application and context into consideration?	How to validate an outcome? How to present feedback to the user? How to present direct feedback during print preparation?

Table 9.1 How-To questions

Sub-Functions	Possible solutions							
Import geometry	STL	OBJ	3MF					
Control geometry	Standard mesh	Cutting mesh	Infill mesh					
Derive user intent	Manual input	Principal component input	Geometry Analysis	Model file data	Intent-oriented print settings	Learning from user input		
Translate user intent	Component profiles	Generalized profiles	Learning from Cura print data	Direct process parameter control	Hypotheses			
Guide the user	List of objectives	Step-by-Step process	Adaptive multiple-choice questions	Checklist	Product configuration system	Visual cues	Animations	Dilemmas
Generate process parameters	Categorical preset controls	Direct process parameter controls	Presets	Visual of result multiple-choice	Adaptive part qualities	Reframing user input		
Present feedback	Visual representation	Notifications	Numbers in perspective	Metaphors	Estimations	Part quality scales		
Lower knowledge threshold	Categorical control	Limited options	Tooltips	Goal-oriented controls	No process language			
Educate the user	Trial & Error	Visual examples	Help database	Tutorials	Social circle interactions	Expert opinions	Seccond opinions	
Manage print jobs	First-come, first serve	Smart planning for efficiency	Prioritized intents	Urgency score	Completion deadline			
Ensure output quality	Validated print profiles	Limited parameter control	Closed-loop control	User feedback	Pre-print test prints	QR-code printing	Print qualities dictionary	Tactile & visual models
Install configurations	Colour-coding	Light indicators	Nozzle and material names	Static configurations				

Table 9.2 Morphological Chart

9.2
Conceptualization

This paragraph first describes how three concepts are generated using the Morphological Chart depicted in the previous paragraph. Next, it outlines the features of these three concepts, and finally it reports how the final design is chosen.

Concept Generation

The Morphological Chart presented in the previous paragraph is used in order to derive principal solutions, or concepts, based on sub-functions for the design. Table 9.3 shows how three principal solutions are derived by combining sub-solutions of each sub-function.

These concepts are:

- **Concept I:** 'Ultimatic', a print preparation method that uses classification learning to determine user intent and propose print settings accordingly.
- **Concept II:** 'Objective', a print preparation workflow based on product configuration systems
- **Concept III:** 'Ultimatum', a method of print preparation using adaptive print preparation

Next, the most important features of these concepts are discussed.

Sub-Functions	Possible solutions							
Import geometry	STL ❶ ❸	OBJ	3MF ❷					
Control geometry	Standard mesh ❸ ❶	Cutting mesh	Infill mesh ❷					
Derive user intent	Manual input ❷	Principal component input	Geometry Analysis ❶	Model file data	Intent-oriented print settings	Learning from user input ❸ ❶		
Translate user intent	Component profiles ❷	Generalized profiles	Learning from Cura print data ❶	Direct process parameter control	Hypotheses ❸			
Guide the user	List of objectives	Step-by-Step process	Adaptive multiple-choice questions	Checklist	Product configuration system ❷	Visual cues ❶	Animations	Dilemmas ❸
Generate process parameters	Categorical preset controls	Direct process parameter controls ❶	Presets ❷	Visual of result multiple-choice ❸	Adaptive part qualities	Reframing user input		
Present feedback	Visual representation ❸	Notifications ❶	Numbers in perspective	Metaphors	Estimations	❷ Part quality scales		
Lower knowledge threshold	Categorical control	Limited options	Tooltips ❶	❷ Goal-oriented controls	No process language ❸			
Educate the user	Trial & Error ❸	Visual examples ❷	Help database	Tutorials ❶	Social circle interactions	Expert opinions	Seccond opinions	
Manage print jobs	First-come, first serve ❸	Smart planning for efficiency ❶	Prioritized intents ❷	Urgency score	Completion deadline			
Ensure output quality	Validated print profiles ❷	Limited parameter control ❸	Closed-loop control	User feedback ❶	Pre-print test prints	QR-code printing	Print qualities dictionary	Tactile & visual models
Install configurations	Colour-coding	Light indicators ❷	Nozzle and material names ❸	Static configurations ❶				

Table 9.3 Concept derivation using the Morphological Chart: (1) Concept I, (2) Concept II, (3) Concept III

9.2.1. CONCEPT I - ULTIMATIC

The Ultimatic concepts applies classification learning in order to derive user intentions and to propose process parameters, printer configuration and material selection.

Ultimatic analyses the model's geometry by slicing it into several layers and records what percentage of the total model's volume is present in each layer. Additionally, the concept takes the ratio between outer perimeter length and area of each layer into consideration. These metrics are used to describe the geometry of different models. Classification is used on these metrics in order to determine a shape recognition algorithm. By learning the relationship between these recognised shapes and print settings, the concept is able to recommend print settings to the user based on the identified shape. Both the shape information and print settings for each print job are stored in the Cloud and are accessible via Cura Connect.

Based on user feedback, the system determines how well the intent of the user is met. The system determines the successfulness of a print in two ways: user interaction and user scores. The user can communicate how well the intended results are being met through interaction by stopping the print process and/or reprinting the same model with different print parameters. Moreover, the user can access the job history of available printers in the environment via the Cura Connect interface to give a satisfaction score that is used by the classification learner to improve its intent-recognition algorithm.

In the prepare phase, the user selects print settings as is the case in the conventional user interaction with Cura. During this process, based on both user input and model geometry, Ultimatic prepares hypotheses about what part qualities the user is trying to achieve. Similar to the patent on user intent deduction and providing relevant computer services (Luciw, Capps & Tesler, 1995) discussed in Paragraph 6.2, the system prepares a set of process parameters, printer configuration and materials to achieve the measured intended results. When additional information is required for the hypothesis, the system highlights print settings the user should interact with to achieve a more accurate hypothesis. The system prompts the user with a notification to conform the hypothesis once it believes the hypothesis is accurate enough. When the user confirms the hypothesis, the system automatically selects the required process parameter, printer configuration and materials.

Required process knowledge is reduced through tooltips that describe how print settings influence the qualities of the resulting 3D printed part. If these tooltips are not accurate enough, the user can follow a short tutorial that explains how to use the print setting to influence the final result via example models.

9.2.2. CONCEPT II - OBJECTIVE

This concept is based on product configuration systems. Paragraph 6.2 has already described how these product configuration systems can be used as an inspiration for intent-based 3D printing approaches. Specifically, the framework for an open configuration system by Zheng et al. (2017) is used.

The Objective concept derives the user intent through a two step process:
First, it leverages the power of third party extensibility of the 3MF file format. When the user exports a model from the create phase, model properties as defined in the CAD software are converted to metrics that are used by the slicing software to filter a set of process parameter profiles that may enable the part qualities defined by these metrics. Moreover, the model is exported as a set of components, rather than a single model, to enable more precise control of the model.
Second, the user is able to select process parameter profiles from the previously filtered list of process parameter profiles for each of the components of the model. Therefore, these profiles are referred to as 'component profiles'. The selection of specific component profiles further defines the user intent.

Component profiles are developed by Ultimaker, companies and individual users to present a subset of print settings that facilitate an intended 3D printed result. Each component profile contains two user interfaces: a 'recommended' interface that is specifically designed to help users select process parameters to achieve the intended part qualities, and an 'expert' interface with a limited amount of manipulable process parameters.
The 'recommended' interface includes images that visualise how to ideally orient models and goal-oriented controls that manipulate multiple process parameters at once. The included visualisations educate the users about ideal model orientations and give the user an impression of how tool paths influence the resulting part qualities.
The 'expert' interface limits the amount of available process parameters to a subset that is known to influence the desired part qualities, but gives the user full manual control over their parameter values.

Because the user can manipulate multiple components of the model individually, the desired configurations of each of these components may conflict with each other. In this case, the user is confronted with a dilemma that presents possible limitations to either of the conflicting component's properties. In doing so, the system ensures that users have a better overview of how their decisions lead to benefits of- and limitations to- the resulting part qualities.

9.2.3. CONCEPT III - ULTIMATUM

The Ultimatum concept prepares the model for 3D printing using a series of visual multiple choice questions. The more questions the user answers, the more accurate the system is able to determine process parameters, printer configuration and materials.

Questions are about physical properties and usage scenarios of the resulting part:
In the case the question is aimed at physical properties, the system slices the model multiple times using different variations of a single process parameter. Next, its presents visual representations of the generated tool paths of each of these slices to the user, as well as metrics that are hard to visualise, such as expected part strength, flexibility and dimensional accuracy.
In case the the question is aimed towards applications of the resulting part, the user is presented with a series of images of 3D printed models used in different scenarios. These models can also be post processed so the system can take material and process requirements for post-processing into account.

The quality of the resulting model is assured by limiting parameter combinations through pre-tested print profiles that define a combination of process parameter values that work well together. Each time the user makes a decision, the model is sliced using a profile from a set of profiles that best matches the series of user choices. A visual of the most recently generated tool path and the resulting part qualities is continuously presented to the user to supply feedback. By looking at how decisions influence the resulting part qualities, users are educated about the influences of process parameters on the printed outcome, and vice versa. Because users select outcomes, rather than the process parameters that lead to them, the amount of required process knowledge is lowered.

9.2.4. CONCEPT CHOICE

Concept evaluation is performed using the Weighted Objectives method (Van Boeijen et al., 2003). Each objective represents a wish from the design criteria described in Paragraph 8.3. The weights for each of these objectives are determined by a cross table (Table 9.4) that determines how the needs relate to each other in terms of importance.

Table 9.5 shows the results of the Weighted Objectives method. The 'weights' column contains the weights as determined by the previously mentioned cross table. Each concept is given scores from 1 to 5 for how well it satisfies the specified wishes, or objectives. These scores are multiplied by the objective's weight to determine the weighted score that is corrected for the importance of the objective. The sum of the weighted scores for each objective represents a total score for each concept.

As shown in Table 9.5, concept 2 is the highest scoring concept and therefore it is chosen as the final concept. The next section describes the further development of this concept by discussing its architecture, user interaction and visual design.

Wishes	Low-cost	Guidance	Future-proof	Satisfaction of specific intents	Flexibiliy	Feeling of control	Educative	Feedback	Operator control	Advanced affordances	Promotion	Printer management	**Total**
Low-cost	1	0	0	1	0	0	1	1	1	1	1	1	**8**
Guidance	1	1	1	1	0	0	1	0	1	1	1	1	**9**
Future-Proof	1	0	1	1	0	0	1	0	1	1	0	1	**7**
Satisfaction of specific intents	0	0	0	1	0	0	0	0	0	1	0	0	**2**
Flexibility	1	1	1	1	1	0	1	1	1	1	1	1	**11**
Feeling of control	1	1	1	1	1	1	1	0	1	1	1	0	**10**
Educative	0	0	0	1	0	0	1	0	0	0	1	0	**3**
Feedback	0	1	1	1	0	1	1	1	1	1	1	1	**10**
Operator control	0	0	0	1	0	0	1	0	1	1	0	0	**4**
Advanced affordances	0	0	0	0	0	0	1	0	0	1	0	0	**2**
Promotion	0	0	1	1	0	0	0	0	1	1	1	1	**6**
Printer management	0	0	0	1	0	1	1	0	1	1	0	1	**6**

Table 9.4 Cross table to determine the weight of each objective

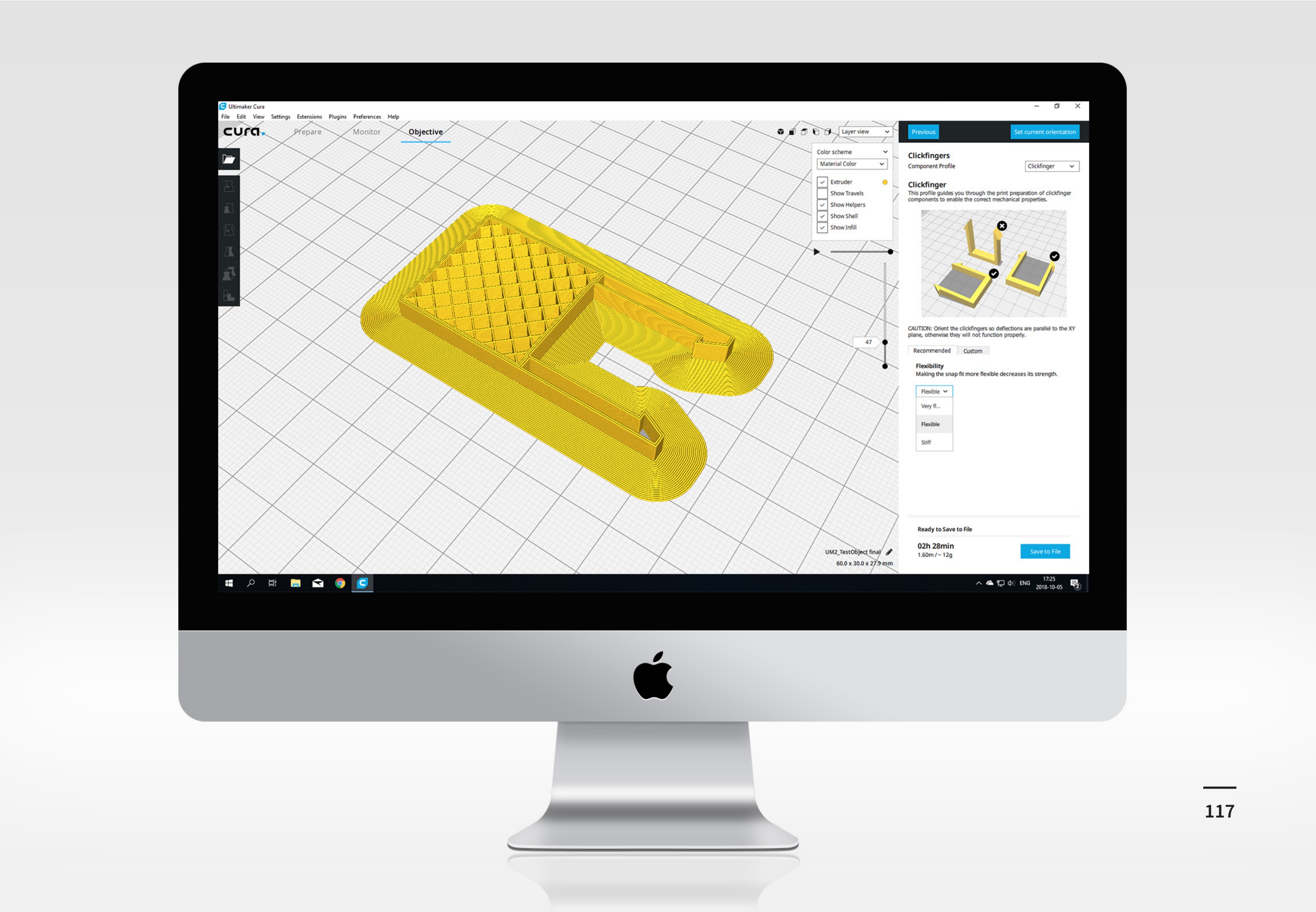
Objectives		Concept I - Ultimatic		Concept II - Objective		Concept III - Ultimatum	
Wish	**Weight**	**Score**	**Weighted score**	**Score**	**Weighted score**	**Score**	**Weighted score**
Flexibility	11	2	22	4	44	5	55
Fleeing of control	10	3	30	5	50	2	20
Feedback	10	1	10	4	40	5	50
Guidance	9	1	9	4	36	3	27
Low-cost	8	4	32	5	40	5	40
Future-proof	7	5	35	5	35	5	35
Promotion of affordances	6	5	30	5	30	5	30
Printer management	6	3	18	4	24	3	18
Operator control	4	1	4	4	16	2	8
Educative	3	4	12	4	12	3	9
Satisfaction of specific intents	2	1	2	4	8	1	2
Advanced affordances	2	1	2	5	10	1	2
		Total	**206**	**Total**	**345**	**Total**	**296**

Table 9.5 Weigthed Objectives method applied to the three concepts

9.3

Final Design

This paragraph dives deeper into different aspects of the Objective concept. The first sub-paragraph presents general information about the Objective concept. Next, the usage scenario is discussed, followed by detailed descriptions of the features that enable this interaction. Moreover, the system architecture and the plugin architecture describe how different constituents of the concept cooperate and communicate with one another. The final sub-paragraph presents the visual design of the Objective plugin based on Ultimaker's brand identity. Together, these sub-paragraphs describe how the Objective plugin cooperates with other hardware products, software packages and databases. However, the final design and the embodiment will be limited to the Objective plugin itself due to the scope of this graduation project.



Clickfingers
Component Profile: Clickfinger

Clickfinger
This profile guides you through the print preparation of clickfinger components to enable the correct mechanical properties.

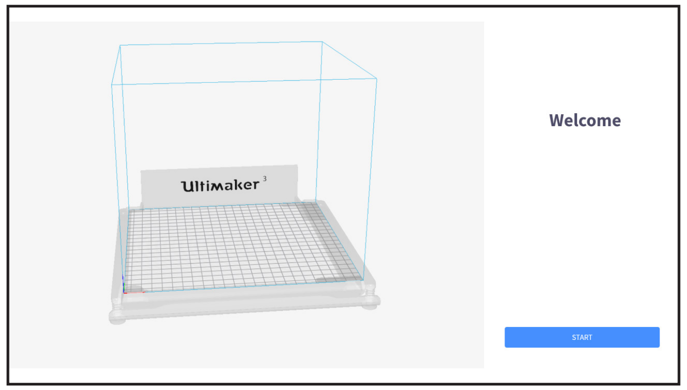
CAUTION: Orient the clickfingers so deflections are parallel to the XY plane, otherwise they will not function properly.

Flexibility
Making the snap fit more flexible decreases its strength.
Flexible

Ready to Save to File
02h 28min
1.60m / ~ 12g

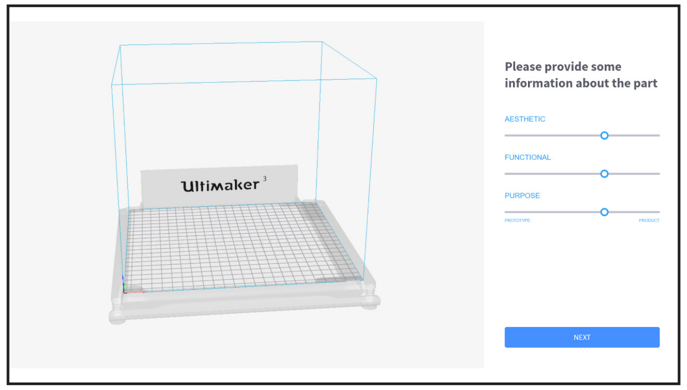
9.3.1. SCENARIO

This paragraph presents the secenario for intent-based 3D printing during the preparation of prints in the slicing software.



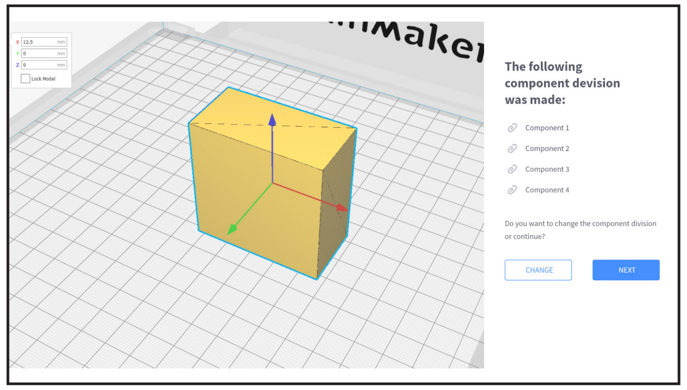
Welcome

STEP 1. The user is welcomed to the user interface and starts the intent-based print preparation



Please provide some information about the part

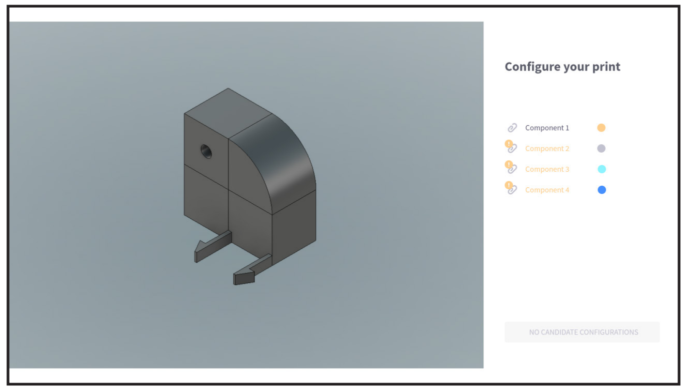
STEP 2. The user is asked to supply information about the general intent of the model, if not derivable from the 3MF model



The following component devision was made:

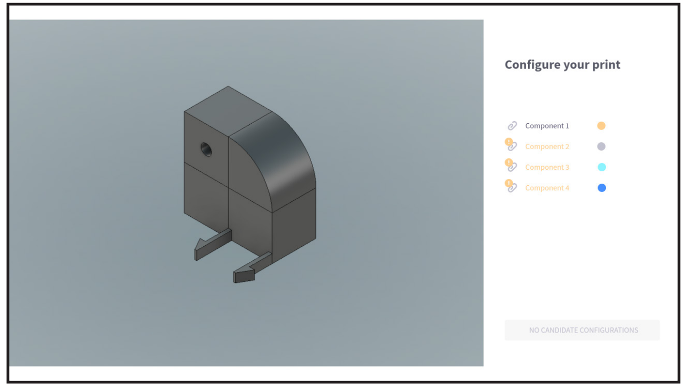
Do you want to change the component division or continue?

STEP 3. Based on loaded file information (.3MF), geometry, and intentions, the model is divided into several components. The user accepts the component division and hits ‘next’.



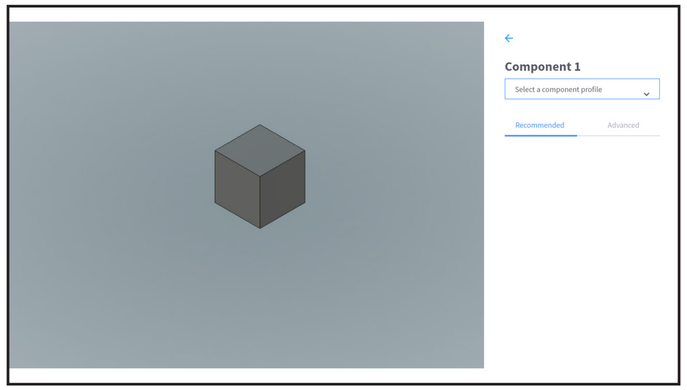
Configure your print

STEP 4. The print highlighted view opens, showing an overview of the print preparation. Currently, there is one complete configuration, Component 1



Configure your print

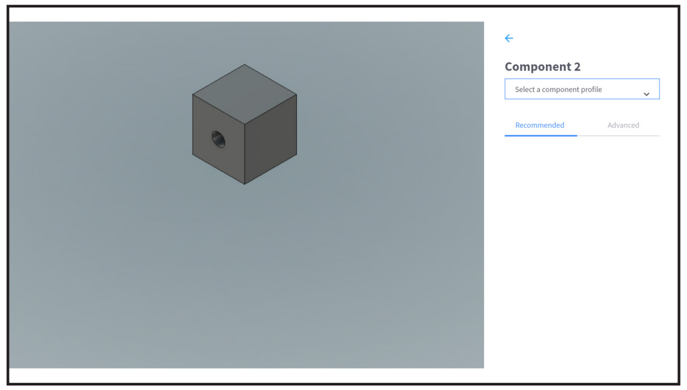
STEP 5. The recommendation engine points the user to components that need additional information to determine candidate configurations via the exclamation mark icon.



Component 1

Select a component profile

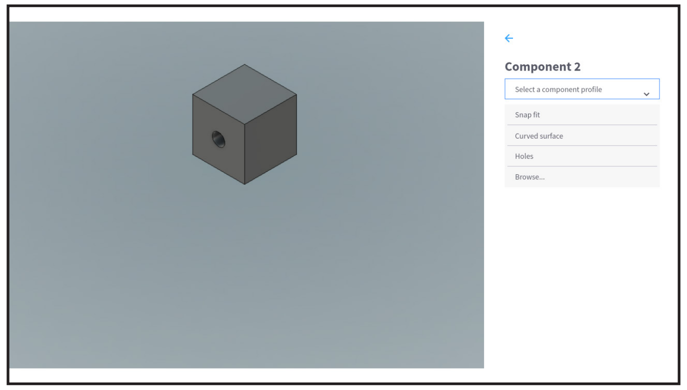
STEP 6. Component 1 is an arbitrary shape. Therefore, the plugin assumes that the configuration for this component is not important.



Component 2

Select a component profile

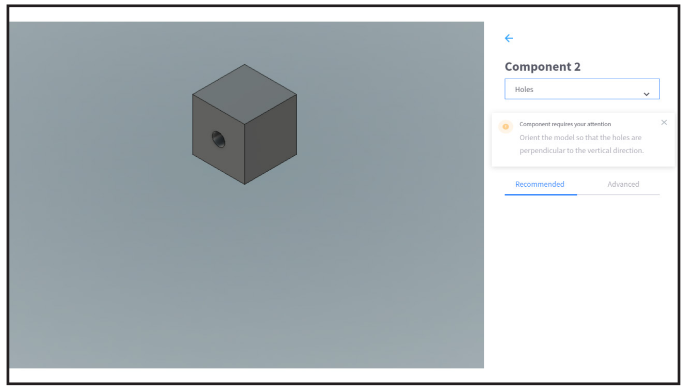
STEP 7. The user selects Component 2 and is taken into the focused view of Component 2.



Component 2

Select a component profile

STEP 8. The user selects a component profile for the component from the dropdown menu. Luckily, a suitable profile, ‘Holes’, is available.



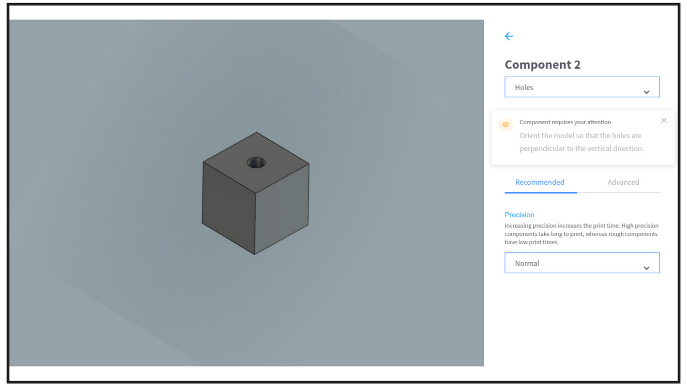
Component 2

Holes

Component requires your attention

Orient the model so that the holes are perpendicular to the vertical direction.

STEP 9. A tooltip shows up alerting the user to take the orientation of the component into consideration.



Component 2

Holes

Component requires your attention

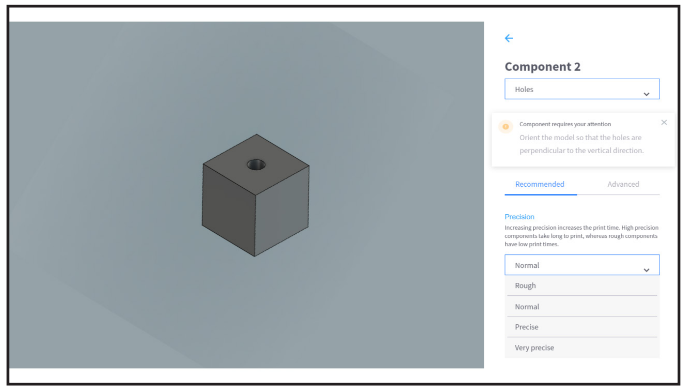
Orient the model so that the holes are perpendicular to the vertical direction.

Precision

Increasing precision increases the print time. High precision components take long to print, whereas rough components have low print times.

Normal

STEP 10. The user changes the orientation of the component according to the tooltip.



Component 2

Holes

Component requires your attention

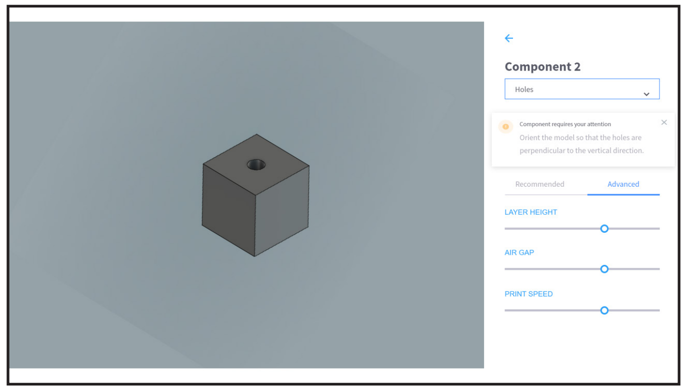
Orient the model so that the holes are perpendicular to the vertical direction.

Precision

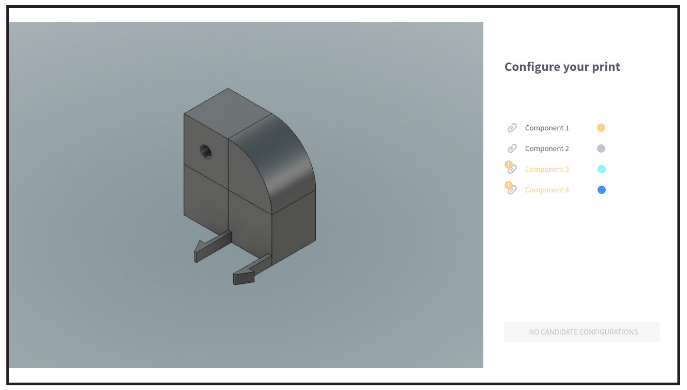
Increasing precision increases the print time. High precision components take long to print, whereas rough components have low print times.

Normal

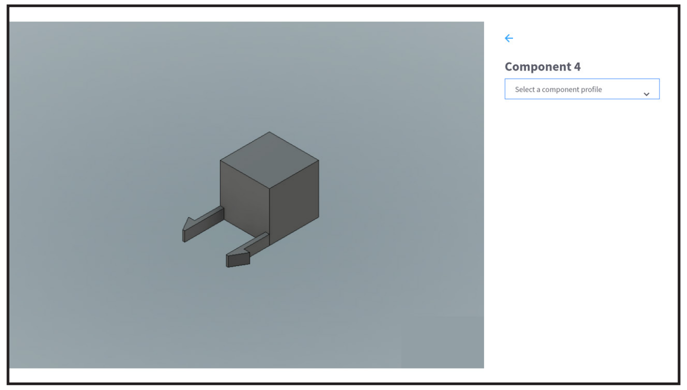
STEP 11. The recommended tab presents the user with important considerations for the selected print profile. In the case of holes, the dimensional accuracy is an important quality.



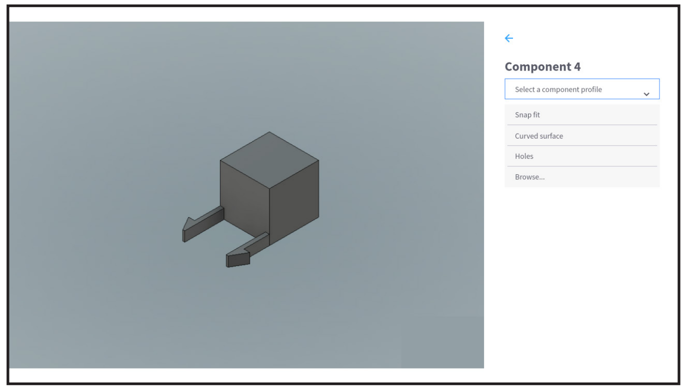
STEP 12. The advanced tab shows relevant print settings filtered by the component profile. This enables precise control for advanced users while focusing only on parameters that matter.



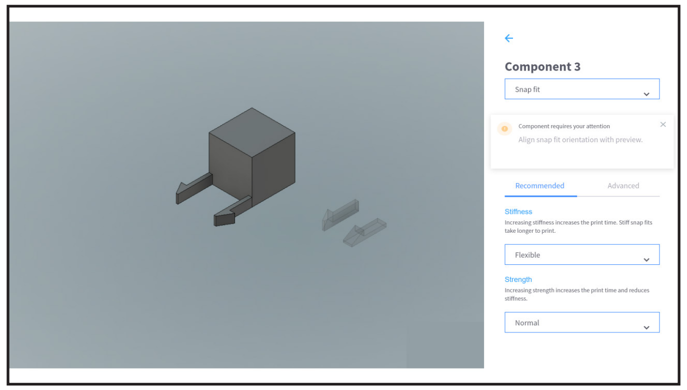
STEP 13. The indicator for Component 2 has changed since the component configuration is complete. The orientation of component 2 is not changed in the highlighted view.



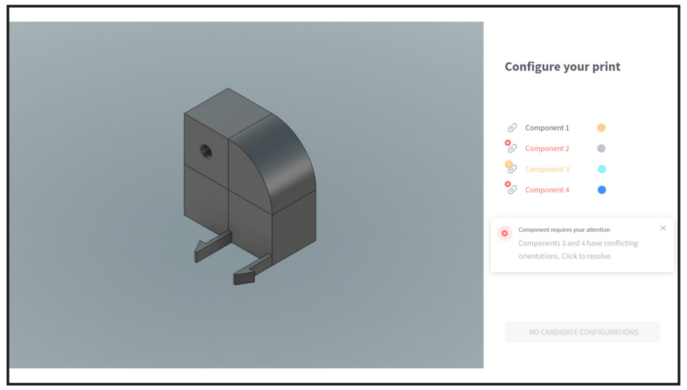
STEP 14. Skipping Component 3, the user selects Component 4 for configuration.



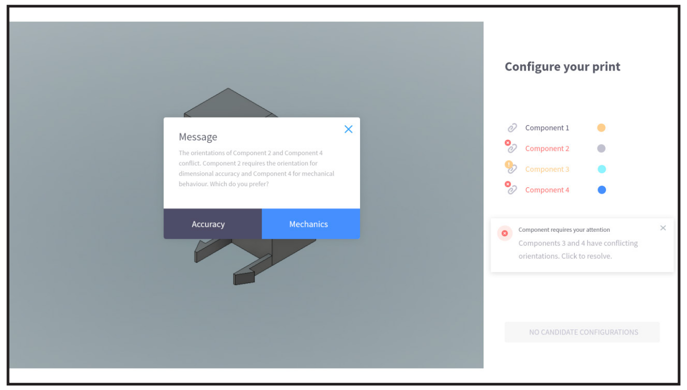
STEP 15. Again, the user selects a profile related to the component, this time the ‘snap fit’ profile.



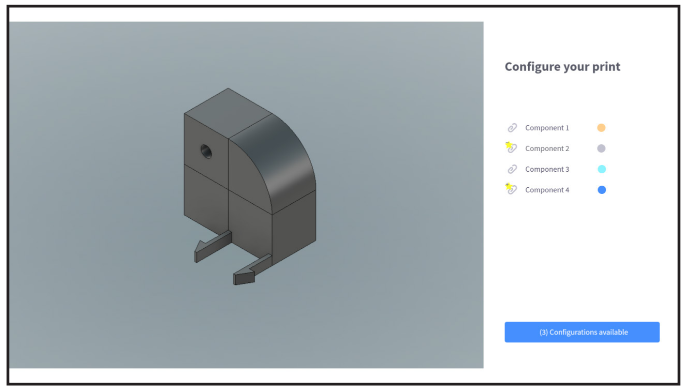
STEP 16. For this particular profile, a shape preview is available in the renderer, indicating two options for orienting the part. In this case, the part is already oriented in the right direction.



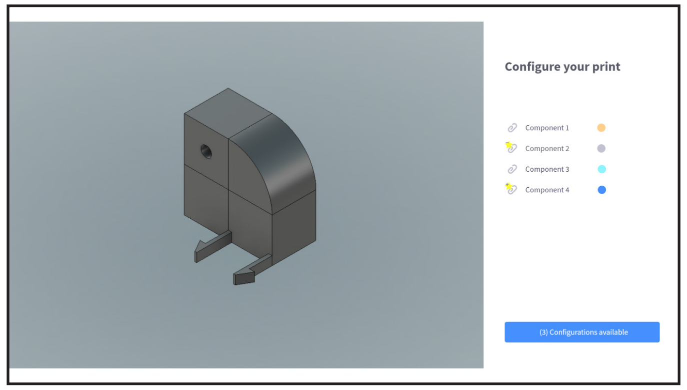
STEP 17. After configuring Component 4, an error occurs because two components now have different desired orientations, while only one can be met.



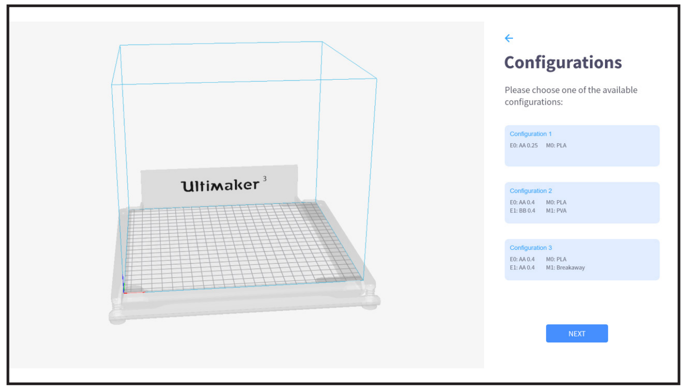
STEP 18. The user selects the error and gets a prompt to choose between two intents related to the profiles of the conflicting components.



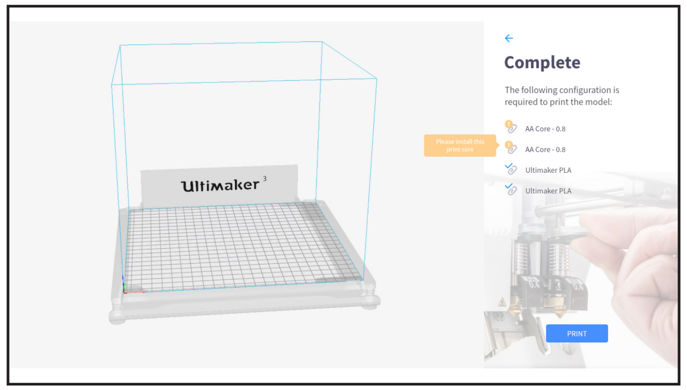
STEP 19. The user selects an option. Consequently, the plugin adapts the desired component orientations accordingly and shows which component is considered more important.



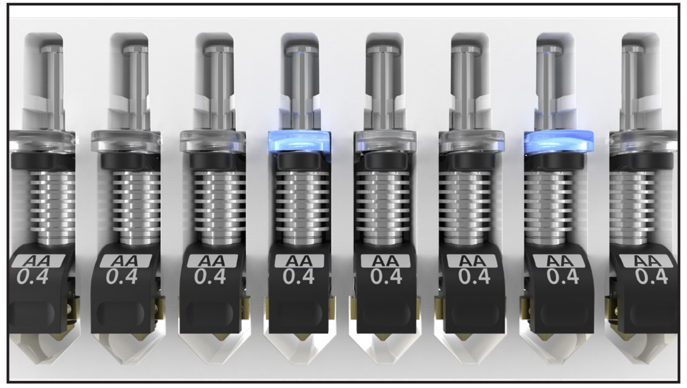
STEP 20. The configuration is now complete and valid, and there are several possible configurations that can achieve the intended results.



STEP 21. The user is presented with possible configurations and can select the one that is most beneficial based on post-processing, print-time, completion-time etc.



STEP 22. Finally, the user is presented with which print cores and materials to print and a colour code used to easily select them.



STEP 23. When the user arrives at the printer, a print core holder indicates which cores to install and the material rack indicates which materials to load based on colour coding.

9.3.2. FEATURE EXPLANATION

The previous sub-paragraph explains how the concept is used. However, the scenario does not describe how the concept is able to facilitate this interaction. Therefore, this sub-paragraph outlines how key features of the concept work.

9.3.3.1 Component-level control

Enabling component-level control in print preparation consists of two steps: first the components and the model need to be exported from the CAD software, and next, these components need to be unpacked in the slicing software.

Exporting the model from CAD is performed by a plugin for CAD packages, like SolidWorks. Popular rendering tools, like Keyshot, use similar plugins to export CAD models to the rendering tool to enable a high level of user control. The plugin for exporting the CAD model's data to the slicing software should include the following information in a data file:

- A mesh of all components combined
- A mesh of each individual component
- Information used for intent deduction

The 3MF data format is used to transfer the listed information from the CAD software to the slicing software. This format, unlike STL and OBJ, allows third party information to be added to the files, which is utilised for communicating extra data about user intent.

Objective imports the 3MF file for intent-based 3D print preparation, and in doing so performs the following actions:

1. It recognises the mesh of all components combined, or base mesh, as a 'normal mesh' (Paragraph 2.3)
2. It sets default process parameters for the base mesh
3. It recognises the meshes of the individual components, or component meshes, as 'infill meshes' (Paragraph 2.3)
4. It generates elements in the user interface that enable users to select component profiles for the individual components

After this process, the user can select the individual components for print preparation using the generated user interface elements and assign component profiles to them to manipulate the ideal way these components are printed. If the selected print parameters for different components conflict with one another, the user has to decide which components will have limited part qualities, to ensure the qualities of other components (see section 5.3.3.5).

9.3.3.2 Intent deduction

As mentioned, the 3MF file can contain information about desired part qualities, information about materials and additional third party data. The Objective plugin utilises this unique feature of the 3MF format to determine information about the intent of the user.

As mentioned in chapter 7, intents in industrial design applications can be grouped described by their aesthetic properties, functional properties and process (or project progress). Functional properties are derived from metrics in the 3MF file that describe these properties, such as strength, flexibility, accuracy, etc. Aesthetic properties are derived from metrics in the 3MF file that describe surface roughness, colour and transparency. Metrics that are used to describe both of these are translated into print settings that influence the properties and thereafter, component profiles that match these properties are recommended to the user. However, the user will still be able to select non-recommended component profiles. Therefore, intent deduction is not an automatic process; the intent information contained in the 3MF file is only used for recommendations, not for automatic selections.

In addition to the intent information contained in the 3MF file, each component profile contains values for aesthetics, functionality, and process. The Objective plugin keeps track of the mean of these three descriptives of all selected component profiles combined. Through this, the plugin is also able to determine recommended component profiles based on project progress.

9.3.3.3 Component profiles

As mentioned in Paragraph 9.2.2, the component profiles are developed by Ultimaker, companies and individual users and contain two user interfaces: a 'recommended' view and a 'custom' view. This section further elaborates on both these interfaces, the management of component profiles and the implications of component profiles for operator control.

Recommended view

Recommended view consists of a number of elements: guiding images or models & goal-oriented part quality controls.

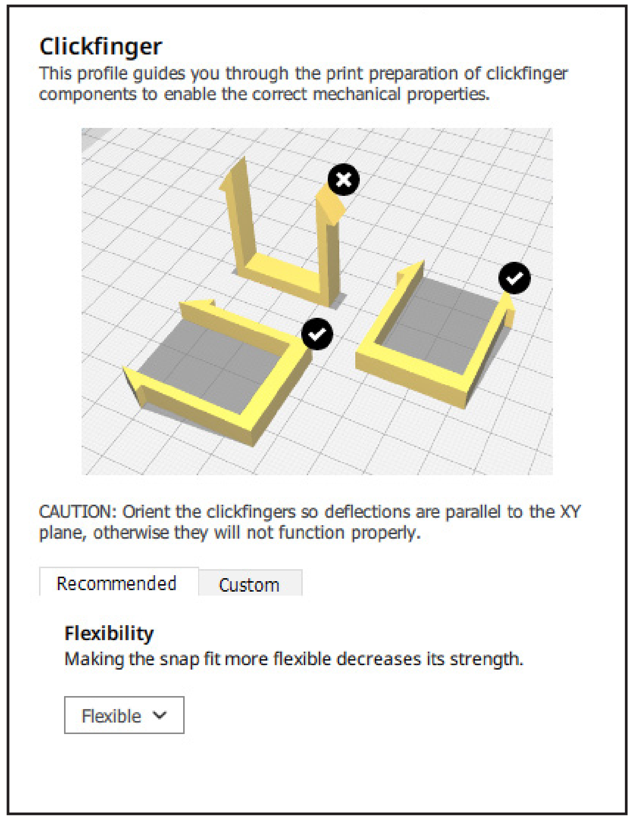
The guiding images or models give users insight into how to orient their model within the build volume (as requested during the exploratory user test), or how part qualities are influenced by manipulating the available controls.

The goal-oriented controls are aimed directly at achieving certain part qualities that are related to the component profile. For example, when printing a click finger (Figure 9.2), an important part quality is the flexibility of the snap fit that facilitates its behaviour. Therefore, this component profile will include a control called 'flexibility', which when accessed, will alter multiple process parameters that influence the flexibility of the click finger at once. By focussing on the end goal, the flexibility of the click finger, rather than the process parameters that influence it, the knowledge threshold is reduced; users do not have to know how- or which process parameters influence desired part qualities. These goal-oriented controls are ordinal, meaning that their values represent ranked categories of print settings. This has several benefits:

1. User selections are limited to a combination of process parameter combinations that work well together to avoid defects in the model.
2. The controls can take the shift in optimum values as a result of combined effects (Paragraph 2.4) into account.
3. The controls can take the law of diminishing returns into consideration to find the optimum parameter combinations for part qualities vs. print time, part qualities vs material usage, etc.
4. Users are protected from printing objects with process parameters that do not significantly benefit the intended part qualities, but do significantly increase print times. For example, when printing an aesthetic model, it is important to have sufficient infill density to ensure that the model is strong enough to be able to handle some impacts. However, excessive values for infill density will negatively impact the experience of the user through increased print time, or the experience of others who have to wait longer before they can print their models.

Custom view

Custom view enables more advanced users to have direct control over a selection of print settings that are known to influence the desired part qualities. The user has the same level of control over these settings as in traditional print preparation, but the chances of misusing print settings due to overconfidence are limited due to the amount of available settings.



Clickfinger

This profile guides you through the print preparation of clickfinger components to enable the correct mechanical properties.

CAUTION: Orient the clickfingers so deflections are parallel to the XY plane, otherwise they will not function properly.

Flexibility

Making the snap fit more flexible decreases its strength.

Flexible

Figure 9.2 Example of a component profile

9.3.3.4 Management of component profiles

Like plugins for Cura, component profiles are available through a browser. The component profile browser collects Ultimaker's own default component profiles and component profiles shared by third parties. Users can also develop their own component profiles for personal use or sharing. Currently, print profiles are shared online by numerous 3D printing enthusiasts, which makes the decision to in part rely on sharing component profiles permissible.

Users can review component profiles and rate them in order to ensure quality component profiles are easy to find. Moreover, Ultimaker can manage a list of recommended component profiles developed by third parties. Additionally, component profiles are highlighted that are likely to match the users' intent using the three Principal Components derived in chapter 7: functionality, aesthetics and process.

Operators that work within companies can manage a company specific component profile browser and thereby set boundaries for how 3D printing is used within the company. Moreover they can select, or develop print profiles that are suitable for preparing 3D printed components often realised in the company's context.

9.3.3.5 Feedback & Guidance

There are several ways in which the Objective plugin gives feedback to users about their preparation process and the influences of their selections on part qualities:

- First, the plugin guides the user towards supplying the system with information concerning the desired component qualities, and consequently desired process parameters. It does so by notifying the user what components need further information when it is not a cubic shape and does not have a component profile assigned to it.
- Second, the plugin helps the user to select the desired process parameters for each component through the information supplied by the interfaces included in the component profiles.
- Third, if the desired process parameters for each of the components conflict, the Objective plugin presents a notification that the components are in conflict, and presents the user with a dilemma. This dilemma urges the user to decide which conflicting component's process parameters to prioritise, which may limit the other conflicting component's resulting qualities.
- Finally, the Objective plugin recommends printer, material and nozzle combinations for printing the model to achieve the desired print qualities (see section 5.3.3.7).

Dilemmas

As mentioned, the dilemmas give feedback on how different components' desired part qualities affect other components. These limitations remain implicit in conventional print preparation because the entire model is configured at once. Therefore the user needs to look for such limitations after changing each process parameter. In contrast, in the Objective plugin, the dilemmas make these limitations explicit by notifying the user what qualities of a component may become limited by pursuing another component's qualities. Through this mechanism the user gains knowledge about which component combinations are permitted, and which ones are not. Users can take this explicit knowledge about conflicting components into consideration when designing their next model for additive manufacturing.

There are several ways in which different component configurations may conflict with one another:

1. Multiple components have different desired orientations, while the base model can only satisfy one of them. Therefore, the user is notified that a conflict has occurred and has to choose one orientation over the other. Alternatively, the Objective plugin could advise the user to separate the model to be printable in both directions (DfAM).
2. Multiple components that exist in the same layer desire different values for layer constant process parameters, such as layer height. In the case of layer height, lower values for the process parameter have a positive influence on part qualities such as strength and aesthetics, but can also have a negative influence on dimensional accuracy (see Paragraph 2.3). Consequently, dependent on whether or not component profiles have been selected that facilitate dimensional accuracy, the Objective plugin may present a notification with a dilemma to the user, or automatically adjust towards the lowest set layer height respectively.

Some settings that are not layer-based, such as infill and amount of contours, can still be set per component and vary within specific layers without causing a conflict.

9.3.3.6 Management of 3D printers & installation of print cores and filaments

Apart from the plugin that is made available for Cura, the concept also describes a couple of supportive tools that enables smarter management of materials and print cores. The first is a multi material supply system that enables machines to be loaded with more than two types of materials at a time. The other is a smart storage unit for unused print cores. Both of these tools enable tracking of installed- and uninstalled nozzles and filaments. The system uses this information to manage print jobs more efficiently, plan maintenance, control material and nozzle supplies, and communicate available printer configurations to the user during print preparation.

Figure 9.3 Print core storage unit indicates which nozzles to install

Unlike the multi material supply system, of which several technologies were discussed in Paragraph 5.2, the print core storage unit introduces a new approach. The print core storage unit enables a data connection to the Cura Connect software and consequently shares data stored on the print cores. This enables Cura Connect to access information about print core usage and calibration. Through this, the print core storage unit significantly improves the user experience in three ways:

1. Users are able to keep track of what print cores are available for use, and whether they are beyond their expected product lifespan.
2. The Objective plugin can communicate the to-be-installed print cores to the user by shining colour-coded light through the transparent handle of the to-be-installed print cores stored in the unit (Figure 9.3). This eliminates the required knowledge of different nozzle types and sizes.
3. All users will eventually be exposed to the educative experience of installing print cores, like during the unboxing experience (Paragraph 4.4)
4. The Cura Connect can use the information shared by the storage unit to recommend nozzles that have already been calibrated to the machine, avoid a lengthy calibration process and enabling users to start their prints directly.

The print core storage unit is a low-cost solution to machine management, since the electronics for data storage, as well as the spring mechanism used to fixate the print cores are already part of the print cores. Therefore, the print core storage does not require moving parts, nor expensive electronics. The electronic circuitry could be limited to physical connections to connect to the print cores, multiplexers to select between print cores to communicate with, a microprocessor to process and manage data and wireless communication.

9.3.3.7 Promoting the use of 3DP affordances

As mentioned in the scenario presented in the previous section, the system determines several printer, print core and material combinations that can be used to print the model to achieve the intended part qualities. Materials to use are derived from the selected component profiles and nozzle sizes and types are derived from the process parameters that result from the user configuration. For example, larger layer heights lead to larger nozzle recommendations and thin line widths lead to smaller nozzle configurations.

Multiple combinations can be suitable for use. Depending on the material and nozzle selection, some alterations may be made to the process parameters automatically. For example, the amount of contours may be reduced when choosing a larger nozzle and the print temperature changed when choosing a different material.

For each of these combinations, the Objective plugin presents value propositions, such as influence on print time, surface quality, strength, cost, flexibility, etc. The Objective plugin also uses information for Cura Connect considering printer availability to determine fastest completion time (the quickest way to realise the model given printer availability).

The printer, material and nozzle combinations are not limited to those that use filaments and print cores that are available in the environment, but may also include filaments or print cores that are not directly available. The Objective plugin stores data of these recommended combinations and the user’s selections. Over time, this data is translated into value propositions of different materials and nozzles aimed at individual users’ or companies’ 3D printing needs. This has benefits for both Ultimaker and the companies that use their 3D printers: Ultimaker can sell more materials and nozzles through the personalized value propositions and companies are able to use 3D printing more efficiently in their processes.

9.3.3. CONCEPT ARCHITECTURE

The previous sub-paragraphs described how the user interacts with the concept and how the different features of the concept work. To enable these features, different segments of the concept need to communicate with one another. This sub-paragraph presents these segments, how they cooperate, and what information they exchange with each other. Therefore, two architectures are presented, the system architecture and the plugin architecture. First, the system architecture presents how different hardware, software and databases share data. Next, the plugin architecture presents the individual segments of the objective plugin, which is part of the system architecture, and how these segments work together.

9.3.4.1 System Architecture

The system architecture of the Objective concept contains several components apart from the plugin itselt. These are:

CAD software
Designers use CAD software to create their models and divide them into several components. The resulting model geometries and assigned properties, are made available to the CAD plugin to package the data.

CAD plugin
The CAD plugin receives the model geometries and the model properties and packages them into a 3MF file containing metrics of desired properties of each component, a geometry of each individual component and the base model geometry.

Slicing software
The slicing software, in this case Ultimaker Cura, provides the engine used for slicing users’ models based on the process parameters communicated through the Objective plugin.

Component profiles local database
The local database of component profiles contains all the component profiles that were downloaded by individuals or those that operators within companies chose to make available to coworkers. These component profiles are downloaded from the component profile browser accessible through the Objective plugin.

Component profile browser
The component profile browser contains component profiles that were developed by Ultimaker or shared by third parties. These component profiles can be reviewed and rated by individual users, as well as recommended by Ultimaker. Based on the desired model properties retrieved from the 3MF file data, a subset of the available component profiles is recommended to the user.

Ultimaker server
An Ultimaker run server is essential in order to maintain a cloud database of component profiles accessible through the component browser.

Cloud database
The cloud database stores copies of component profiles developed by Ultimaker, as well as component profiles shared by third parties. The component profiles stored on the cloud database are available through the component profile browser.

3D printers
The 3D printers in the environment detect their installed print cores and filaments, as well as their job status and share this data via Cura Connect.

Cura Connect
Cura Connect manages a cluster of 3D printers and the print jobs by maintaining information about printer configurations, print job progress, print job queues and available materials and print cores in

the environment. Cura Connect receives this data via the connected 3D printers and the print core storage unit. It shares this data with the Objective plugin for making improved recommendations for printers, materials and print cores to use. In reverse, the Objective plugin shares information about new print jobs and the required printer, materials and print cores combinations.

Multi-material supply system
The multi material supply system determines what filaments are loaded using NFC sensors and communicates this data to the 3D printer it is attached to.

Print core storage unit
The print core storage unit identifies what print cores are installed into it, how they are calibrated and for how long they have been used for printing. It sends this data to the Cura Connect interface. Moreover, it can receive data from the Objective plugin (via Cura Connect) for highlighting certain print cores for installation using colour-coded LED lighting.

9.3.4.2 Plugin architecture overview

The architecture of the Objective plugin contains several modules. These modules are:

- **Design Assessment Module**
This module assesses the design geometry to identify curvatures in the model geometry, required support and ideal part orientation.
- **Recommendation Engine**
This module recommends the user to change configurable options to gain a printable file that meets the user's requirements.
- **Requirements Deduction Module**
This module captures the user intent and determines model requirements according to the user intent.
- **Visualization and Selection Engine**
This module presents information from the other module to the user in separate viewing modes.
- **Validation Engine**
This engine validates whether the printed geometry meets the requirements set by the user.
- **Help Module***
This module is designed to educate the user about the influences of process parameters on the result. Moreover, it systematically introduces new learnings for the user based on the printed models.

In this framework, a configuration can both be complete or incomplete and valid or invalid. A configuration is complete when all information required for the system to make a configuration is supplied by either the user or scripts. A configuration is valid when it meets the requirements as set by the user.

*Because an informative plugin is already being developed internally at Ultimaker, the help module is deemed beyond the scope of the project.

Next, the individual modules and their in- and output are discussed in separate sections.

Requirements Deduction Module
The Requirements Deduction Module takes the user intent as an input to develop a feature model. The feature model is a description of the requirements and wishes of the user. The requirements are output to the Validation Engine in order to check which possible configurations meet the user's needs. Additionally, the wishes are output to the recommendation engine in order to rank possible configurations.

Apart from the automatic deduction of wishes and requirements based on the user's intent, the system also offers users the possibility to manually add or adapt wishes and requirements if necessary.

Recommendation Engine
The Recommendation Engine translates the user requirements for the different components into recommended process parameters, material selections and print cores. Moreover, if conflicts arise, the Recommendation Engine determines a series of considerations that the user must take on a component basis to reach a complete valid configuration.

Validation Engine
The Validation Engine checks the process parameters that are set in each component's configuration for conflicts with other component configurations. How it manages this is described in the previous section. Additionally, the Validation Engine determines whether there is at least one possible printer, material and nozzle combination that meets the process parameters set in configurations. If no conflicts occur and there is at least one printer, material and nozzle combination that meets the requirements, the Validation Module sets the configuration as valid and the user may continue towards selecting a proposed printer configuration.

Design Assessment Module
The Design Assessment Module takes care of importing the 3D models from the 3MF file and determining the base mesh and the component meshes. It shares the data of the imported component meshes with the Visualisation & Selection Engine to create user interface elements for these components.

Visualization & Selection Engine
The Visualization & Selection Engine is in charge of rendering the user interface, which includes rendering different controls in the sidebar and presenting two model view options to the user: 'Highlighted View' and 'Focused View':

Highlighted View
The Highlighted View highlights different components and their 'classification'. By assigning components the same classifications the user is able to prepare multiple components at once using the same component configurations. In addition to their classification, the Highlighted View points out whether components require the user's attention to achieve a complete configuration by checking if it has a component profile assigned to it.
The Highlighted View also enables control of some print parameters of the base model that are related to the printability of the model, such as support- and bed adhesion structures.

Focussed View
The Focused View shows individual components in an independent orientation from the base model. This allows the components to be 'sliced' in an ideal, 'desired' orientation. Of course, the base model geometry can only have one orientation and therefore components with different desired orientations cause conflicts (see Validation Engine). The configurations made in the Focused View only serve as a means to select the best-case process parameters for the plugin to consider. Of course the plugin tries to satisfy most of these desired parameters

9.3.4. VISUAL DESIGN

To develop a design for the user interface, one needs to first consider the corporate identity; brand values and visual identity. First the influence of the corporate identity on the visual design system is discussed. Subsequent sections discuss how iconography and typography contribute to the visual design system of the intent-based 3D printing plugin. Additionally, wireframes are presented for the user interface. Finally, all components of the visual design system are used to create the visual design of the intent-based 3D printing plugin.

Corporate identity

As mentioned in Paragraph 2.1, Ultimaker's corporate values are: leading, reliable and accessible. Additionally, a brainstormwas conducted on the Ultimaker brand identity through adjectives that describe the company's culture, customers, voice, benefits and unique qualities using the CORE method by Chris Do and Jose Caballer (TheFutur, 2014). The most important characteristics of the Ultimaker brand that result from the brainstorm are presented in Figure 9.4. It would be beneficial to communicate these characteristics through the visual design of the Objective plugin.

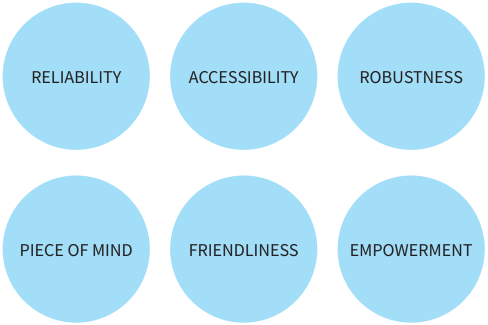
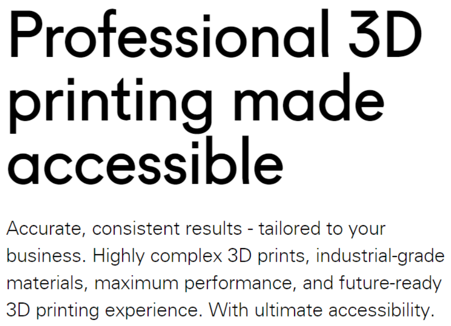


Figure 9.4 Key characteristics for visual design

Typography

Ultimaker's website (Ultimaker, n.d.) currently uses typefaces that are selected for the Ultimaker brand identity: Univers and a personalised version of Fugue (Figure 9.5).



Professional 3D printing made accessible

Accurate, consistent results - tailored to your business. Highly complex 3D prints, industrial-grade materials, maximum performance, and future-ready 3D printing experience. With ultimate accessibility.

Figure 9.5 Fugue (heading) and Unviers (body) in use on Ultimaker.com

Since the Cura software is available as open source software, it uses different typefaces. In the past, the Ultimaker Cura software has relied on system fonts or the Proxima Nova typeface when downloaded from the Ultimaker.com website on a Mac. The current version of Ultimaker Cura, version 3.4, uses the Noto Sans typeface developed by Google Inc (Figure 9.6). The Noto Sans font is available in multiple styles and weights, supports all languages and is freely available to all (Google. n.d.).

Although Noto Sans is a geometric typeface, there are more suitable alternatives available in terms of the design of the letterforms. An option is the Circular Std. typeface designed by Vladimir Mechkauskas (Figure 9.7). Like Noto Sans, the font is licensed for free commercial use. Compared to Noto Sans, the geometric shape of the letterforms of the Circular Std typeface appear more friendly, modern and closer to the personalised Fugue typeface used on the Ultimaker website. The downside of Circular Std is that is does not come with the broad language support of Noto Sans. However, as a concept typeface to use in future iterations of the Cura interface, Circular Std is used in the final visual design.

Figure 9.6 Noto Sans

Figure 9.7 Circular Std. (used in the Objective plugin)

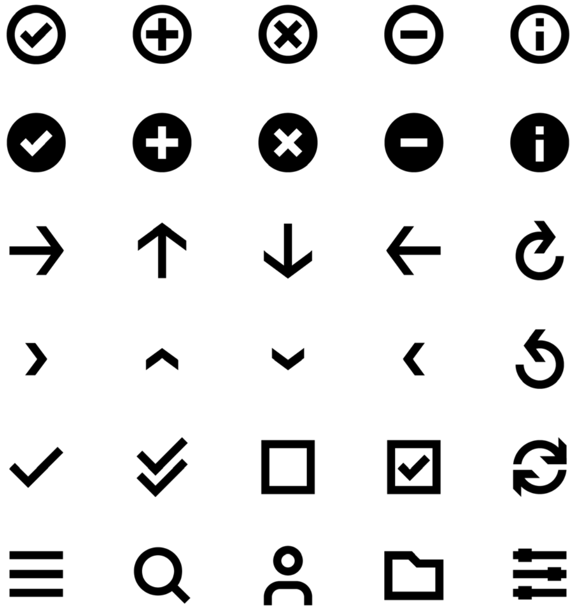
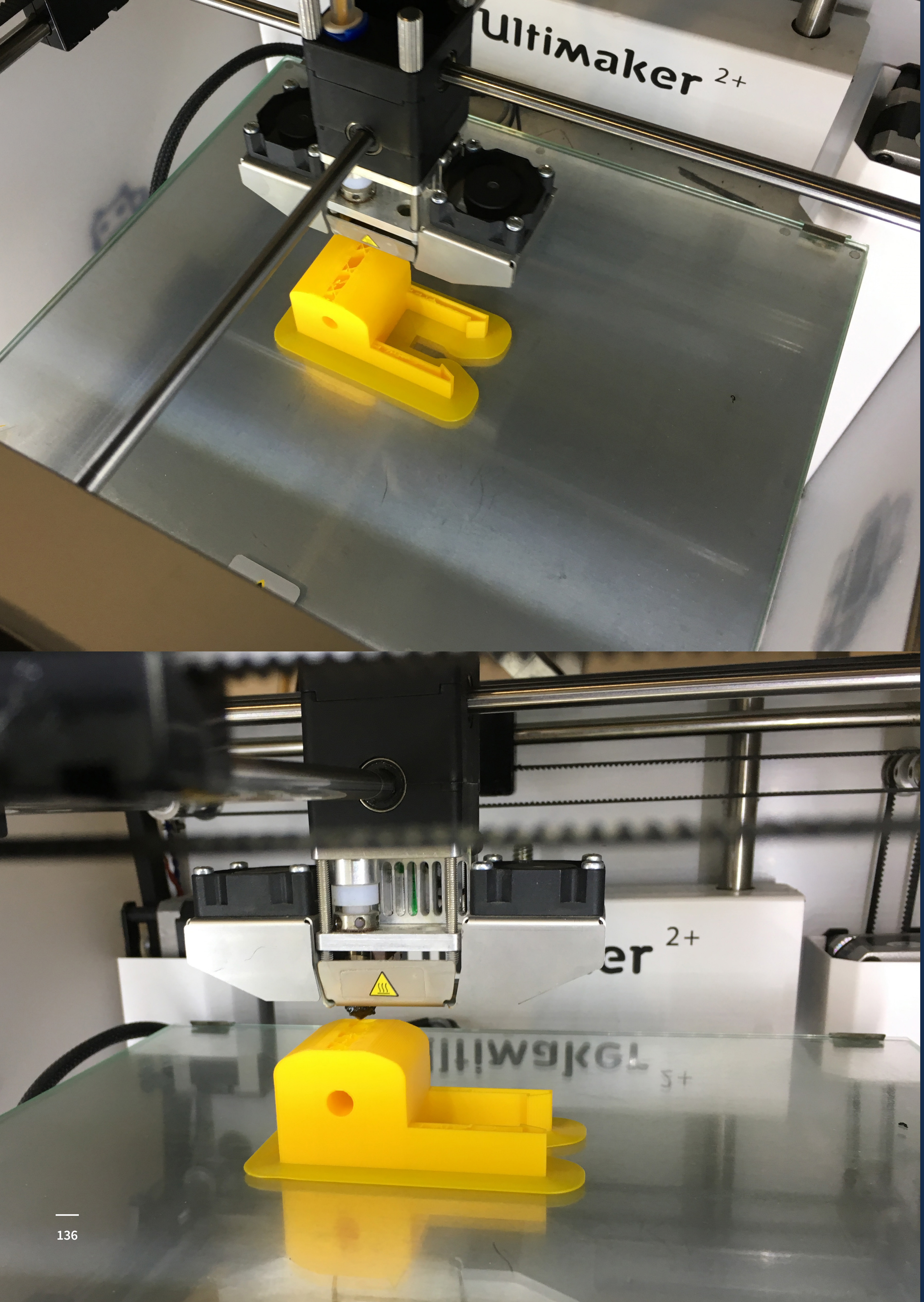


Figure 9.8 Icons for the Objective plugin

Iconography

The icons used in the Cura interface do not appear to follow design guidelines since they use different stroke widths, sizes and border radii. In order to create a peaceful aesthetic, the iconography will need to be more consistent by using such design guidelines. Therefore, a new set of icons was designed using a grid system. Due to the scope of this thesis, the icons are limited to icons that are used by the final concept and are not yet optimised for proper pixel-scaling and black & white inversion. A subset of the new icons is displayed in Figure 9.8. The state of the icons is displayed by varying stroke width, fill, colour and opacity. Depending on the importance of the icon and its location in the user interface, these attributes can be used to guide the user's attention towards the icon.



10.
Embodiment

This chapter describes how a prototype of the plugin for intent-based 3D printing was made in Cura. This plugin has its limitations due to the scope of this study. Front-end and back-end structure of this plugin are described, as well as its component profiles. This chapter concludes with important challenges for the embodiment, that partly need to be resolved in the future.

10.1
Programming

Cura is built using the Python 3 object-oriented programming language for the back-end and Qt for the front-end, or user interface. Since Cura is an open-source project, its source code is freely accessible to any user via Ultimakers' GitHub repository. Additionally, some to-be released plugins served as inspiration for this plugin's embodiment. Both JetBrain's PyCharm and Notepad++ were used to write the plugin on a computer with a Windows 10 operating system and Python 3.7 installed.

Setting the scope for the embodiment

The prototype aims to test the user interaction of assigning component profiles to parts of the model in order to achieve intended results. Because orientation of the model plays an important role in this, it is also included. The realized plugin simulates steps 1 and 5-17. Due to the scope of the project, the realized plugin has the following limitations:

- There is not shape recognition implemented.
- Information sent from the create phase via the 3MF file is not taken into account. The components are separated and manually named or called Object 2, Object 3, etc. The first component, Object 1, is always reserved for the base. The base is a single geometry of all components merged together to ensure that every component overlaps with the base.
- Only a single extruder can be used to print the object.
- The determination of possible configurations is not part of the plugin.
- The assignment of nozzle and material is not part of the plugin.
- Changing of layer-constant settings, such as layer height, is only supported through changing the print profile of the base, which are the standard Ultimaker print profiles available per printer type.
- The presented visual design of the Objective plugin is not implemented in the plugin.

The next paragraphs discuss how the plugin was realized in Cura, and according to what structure the back- and front-end of the plugin work.

10.2
Front-end structure

Cura allows several types of plugins to be developed. The intent-based printing plugin is developed as a 'CuraStage'-type, meaning that a new tab is made available for the user. When the user clicks on this tab, a new interface is opened. The top menu and the toolbar on the left remain accessible, as is the scene, but the rest of the interactable elements are removed. The plugin uses this blank space to create a custom sidebar that enables the intent-based print preparation.

The sidebar is filled with several TabViews. Through using these TabViews, the sidebar's real-estate, or part of it, can be treated as a Tab. As the name TabView suggests, every Tab is treated as a new view. By manipulating the index of the TabViews, the plugin can control what views are presented to the user. Figure 10.1 shows how these TabViews are implemented in the intent-based printing plugin.

mainTabView and componentTabView

The mainTabView controls the main-structure of the plugin, containing the following Views:

- **Introductory view:** This view is used to check whether the user has loaded a model. When pressing start, the models on the build plate are registered and the user is taken to the highlighted view.
- **Highlighted view:** The highlighted view is used to give the user access to the individual components that are made available within the model as individually configurable mesh-types (more on this later). Moreover, it presents possible conflicts between desired component orientations and component settings. Additionally, it presents some controls that are relevant to how the entire object is printed, such as for generating support material and extra build plate adhesion measures. Finally, when the user has configured the components of the model properly, the highlighted view presents the number of available configurations to choose from.
- **Focused view:** The focused view contains the componentTabView. This TabView contains a Tab for each individually configurable component. Depending on the component selected in the highlighted view, the user is taken to the focused view presenting the tab of that component's configuration.
- **Configuration view:** The configuration view presents the user with the configuration options that are available and meet the requirements set beforehand. Here, the user makes the final decision of which material to print with and with what nozzle to do so.
- **Finish view:** The finish view presents the user with the actions he or she needs to take in order to print the model. The user is told what materials and print cores to install in order to print the resulting G-code file.

While the support for the last 2 of these views is included, they are not functional at this stage.

profileTabView and settingTabView

The structure is further complicated by the fact that every component Tab must be able to present different component profiles. Therefore, a profileTabView is included. Moreover, within these component profiles, different setting views (recommended and custom) should be visible. Therefore, each profileTab in turn contains a profile tabView which in turn contains a settings TabView.

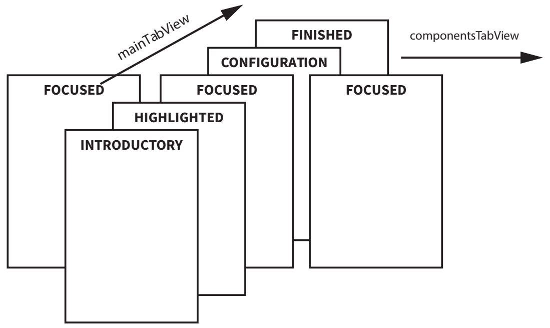


Figure 10.1 mainTabView and componentsTabView

10.3
Back-end structure

This paragraph presents the functionality of each of the classes that contribute to the functionality of the intent-based 3D printing plugin.

ComponentsModel.py

The componentsModel, as the name suggests, identifies the different components in the scene as instances of the SceneNode class. The SceneNode class is a standard class used in Cura to represent nodes in the scene to enable basic, often used functions such as movement and geometry representation, which the intent-based printing plugin builds upon. Moreover, the ComponentsModel determines the base node by selecting the node with the largest bounding box in the scene. Since all other components are just a part of the entire model's volume, the base node always has the largest bounding box.

Tasks:
- Maintains a list of configurable components

Determines the base node

ComponentDecorator.py

As mentioned, the ComponentsModel class distinguishes different components in the scene and adds them to a list of instances of the SceneNode class. In order to add extra functionality to these nodes, they are given additional decorators. A decorator is an extra class that can be attached to a node to enable additional functions (as defined in the specific decorator class applied). The ComponentDecorator is such a decorator, which as the name suggests is attached to each node that represents a component in the scene. This ComponentDecorator class is used to store information about the selected component profiles, selected print settings and the (preferred) orientation of the component it is attached to.

Tasks:
- Adds additional functionality to each component

IntentPrintingStage.py

The IntentPrintingStage is the core of the plugin, representing the new workspace in which the intent-based printing plugin is built. Apart from creating this new environment for the plugin, a key functionality of the IntentPrintingStage is to ' expose' itself to the user interface built on Qt. By exposing itself to the user interface, the interface can use models defined in the ComponentsModel and ProfilesModel to create tabViews and access data that is stored in the Python environment.

Tasks:
- Creates the Intent printing stage
- Exposes python scripts to Qt for communication between the back-end and front-end
- Maintains instances of the ComponentsModel, ProfilesModel, RecommendationEngine, ValidationEngine

ValidationEngine.py

The main task of the ValidationEngine is to determine whether the current settings and desired orientations of the components do not conflict with each other. Different desired component orientations cannot result in a valid configuration, because the base that they are a part of can only assume a single orientation. An invalid solution can also occur when two components that exist in the same layer prescribe different values for layer-constant settings, such as layer-height. Therefore, the ValidationEngine also determines components that overlap with each other.

Tasks:
- Checks whether incompatibilities occur because components have different desired orientations
- Checks whether incompatibilities occur because different components in the same layer prescribe different values for layer-constant settings
- Determines whether components exist within the same layer

RecommendationEngine.py

The RecommendationEngine is currently not functional in the plugin. If functional, the RecommendationEngine is in charge of making sure that the user provides information required to determine possible combinations of printer configurations and materials that can be used to print according to the user's intent. When selecting different configurations, it is also in charge of calculating changed parameter settings. For example, when the user was initially configuring for a 0.4 mm nozzle, but selects a 0.8 mm nozzle configuration, the wall line count should be halved to compensate for the wider lines of material that are deposed by the larger nozzle.

Tasks:
- Determines required user actions in order to achieve a complete configuration
- Advises and guides user based on his or her intent
- Determines print configurations and material for printing with the current user demands

ProfilesModel.py

The ProfilesModel detects folders in the plugin's 'profiles' subdirectory as a component profile and stores them in a list of component profiles. It uses the information provided by each component profile to present information about setting visibility to the PerComponentsVisibilityHandler, which is discussed next.

Tasks:
- Maintains a list of the available print profiles in the profiles directory

PerComponentVisibilityHandler.py

The PerComponentVisibilityHandler is in charge of the setting visibility of individual components. The visible settings are derived from the selected component profiles.

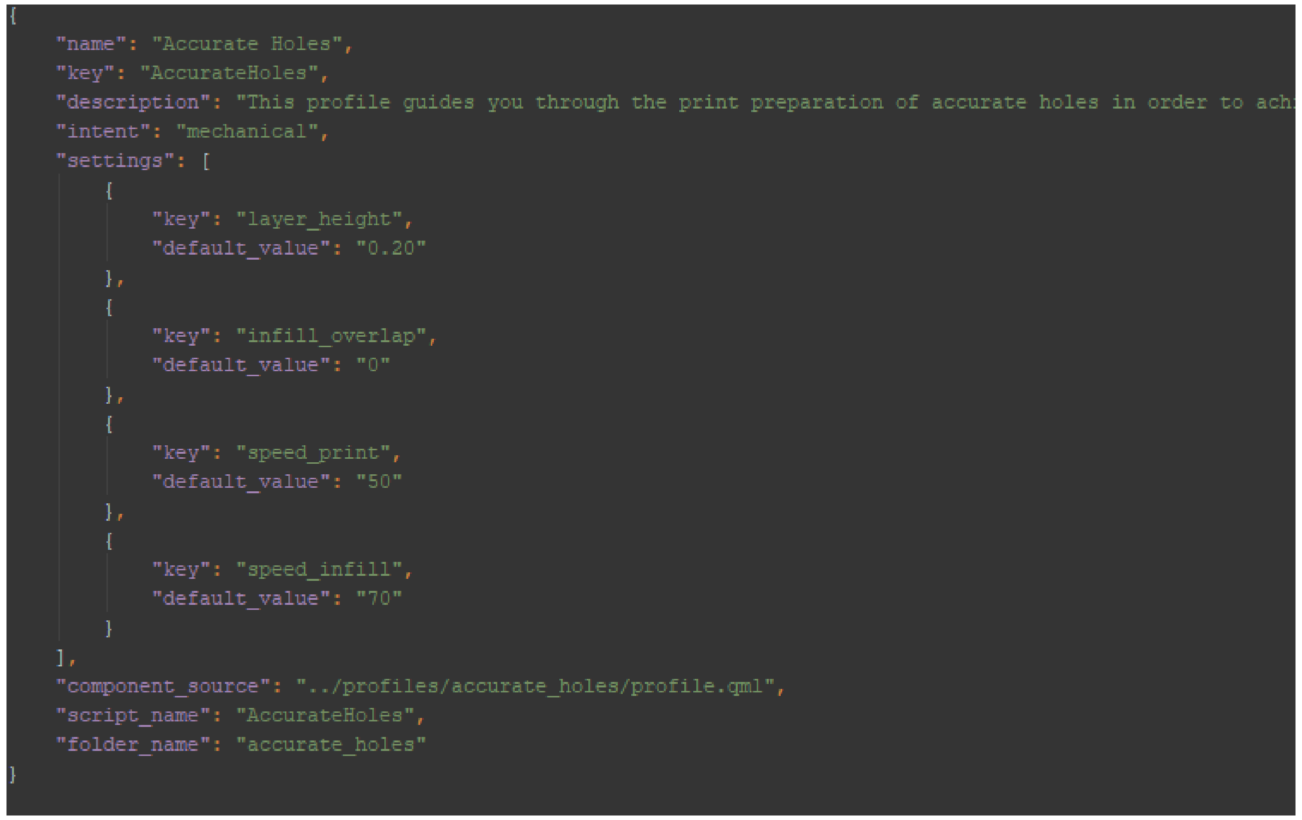
Tasks:
- Filters visible print settings based on selected component and selected component profile

10.4
Component profiles

Component profiles are gathered in the 'profiles' directory of the plugin's root folder (which contains the Python scripts). Each profile is delivered in a folder with a unique name, containing several items:

- A config.json file
- A profile.qml file
- An assets folder
- A components folder
- A plugin-specific Python script containing functions

The config.json file (see Figure 10.2) contains information about the component profile. Naturally, the config file includes the profile's name and it's description. Additionally, the component profile contains information about intent through scores ranging from 1 to 5 for the aesthetic-, functional- and process- variables. These variables will be used to make a pre-selection of the component profiles, but are currently unused. Moreover, the profile contains a 'component_source' which is a path that refers to a QML file containing the visuals to be presented in the recommended view settings. The 'script_name' and 'folder_name' are currently used to locate the profile-specific Python script with functions related to the component profile. However, these could be eliminated in the future by implementing a script that can find component profile Python scripts in a more adaptive way. The settings 'key' contains information about what settings should be visible to the user, as well as information about their default values when the profile is selected.



```
{
    "name": "Accurate Holes",
    "key": "AccurateHoles",
    "description": "This profile guides you through the print preparation of accurate holes in order to ach
    "intent": "mechanical",
    "settings": [
        {
            "key": "layer_height",
            "default_value": "0.20"
        },
        {
            "key": "infill_overlap",
            "default_value": "0"
        },
        {
            "key": "speed_print",
            "default_value": "50"
        },
        {
            "key": "speed_infill",
            "default_value": "70"
        }
    ],
    "component_source": "../profiles/accurate_holes/profile.qml",
    "script_name": "AccurateHoles",
    "folder_name": "accurate_holes"
}
```

Figure 10.2 config.json file of a component profile

10.5
Challenges

Apart from the difficulties with learning new coding languages and understanding the Cura source code, several issues arose that presented a challenge for the embodiment. Next, major challenges for the embodiment are discussed:

Infill mesh & cutting mesh

As mentioned before (paragraph 2.2), the infill mesh type enables the user to set settings for the infill of overlapping models, whereas the cutting mesh enables the user to choose new settings for the entire overlapping volume. The cutting mesh creates visible seams at the component boundaries. These seams are undesirable for both part strenght and aesthetics. In case an object is printed in a single material, the infill mesh is therefore the most beneficial option. However, for printing components in different materials, the cutting mesh is required.

The infill mesh does not only come with benefits, but also with challenges. One of these challenges is the management of outer perimeter widths and top- and bottom thickness. Certain components, like snap fits, benefit from having no top and bottom layers since these layers will negatively affect flexibility. Moreover, in order to make the most flexible snap fit possible, a single outer wall line needs to be used. This results in a situation where it is beneficial to have no top and bottom layers defined in the base mesh in combination with only a single perimeter wall. At the same time, the top/bottom wall thickness of the infill mesh are set to zero, as well as the amount of perimeters.

The user can adapt this starting point to make the snap fit less flexible by changing settings of the component mesh, thus the infill mesh. However, when increasing the amount of walls, it is more beneficial to do so on the base mesh, since this will result in a stronger and more aesthetically pleasing part. Therefore, it would be beneficial to adjust the number of perimeters of the base mesh to the minimum number of perimeters found in the component configurations, and consequently lower the number of perimeters of all infill meshes by the same amount. Applying such automatic adjustments causes a disconnection between what a user sets as a value for the infill mesh, and what setting is actually applied to the infill mesh. This can cause the user to doubt whether the setting has been selected correctly, especially in custom mode.

Multiple infill meshes

For a long time during the development of the intent-based 3D printing plugin an issue persisted that caused the infill meshes to double the amount of wall lines specified by the user input. In the final stages of the development of the plugin, these issues were solved. A bug in the script that ungrouped the models in the 3MF file caused the models to be copied, without deleting the original nodes. Therefore, a double of every component existed in the scene and both of these components would be configured at the same time, causing some settings, such as number of wall lines, to appear to be doubled. This doubling of components also caused Cura to crash when one of the paired components was deleted.

Communication between back-end and front end

The communication between the front -end and the back-end of the the plugin was problematic due to the lack of experience with coding in the Qt programming language. This caused the plugin to be unable to show different user interfaces in the recommended tabs of the component profiles. This inability to dynamically change part of the user interface depending on the selected component profile likely introduced a bias in the results of the first validation study (see next chapter). Since the issue has been solved, a second user test with additional improvements has been conducted.

10.6
Unresolved issues

Several issues in the plugin's source code could not be solved in the timeframe of this project. It is strongly advised to resolve these issues in the future. The issues that can occur in the current state of the plugin are the following:

- In its current state, the plugin does not support dual extrusion machines. A bug in the python code prevents settings to be loaded correctly which causes the model to be printed with an infill density of 100%.
- The Cura log file states that for some configurations part of the tool path is missing. However, prints made using the intent-based 3D printing plugin do not fail. There has been no further investigation of the issue, since the issue did not influence printability of the generated Gcode files.
- The previously mentioned challenge of automatically adjusting the number of perimeters of the base mesh depending on the minimum amount of walls desired in the component infill meshes remains. It is recommended to enable the user to control the sum of the number of the perimeters of the infill mesh and the base mesh through a single setting. In doing so, the system can automatically determine the number of perimeters of the base mesh and the infill mesh without changing values set by the user (Paragraph 10.5).

11.
Evaluation

Two user tests were conducted in order to validate the model. The results of the initial user test were invalid since the prototype plugin contained a number of errors that influenced the end result. Therefore, a second user test was conducted with an improved version of the prototype, which is described in this chapter.

11.1
Introduction to the user test

This user test was conducted to validate whether the component-level control using component profiles has the desired effects on 3D print preparation as described in paragraph 8.3. Therefore, the study compares the conventional method for 3D print preparation, as in Ultimaker Cura v3.3.1, with the method of 3D print preparation using the prototype Objective plugin. The study aims to answer the following research questions:

Research question
How does intent-based 3D printing using the Objective plugin compare to the conventional print process as implemented in Cura?

In order to answer this research question, the following sub-questions are posed:

1. How much control is experienced using the two methods of 3D print preparation?
2. What method of 3D print preparation is expected to give the best results regarding satisfying the intended part qualities?
3. What is the perceived difference in knowledge transfer, or “educativeness” between the two methods of 3D print preparation?
4. How does the prototype plugin influence the amount of guidance supplied during 3D print preparation?

For these sub-questions, the following hypotheses are posed:

1. Users experience more control over the model, but reduced control over process parameters, when using the prototype plugin compared to when the conventional method of 3D print preparation.
2. Users have more confidence in the resulting part qualities when using the prototype plugin compared to when using the conventional approach to 3D print preparation is used.
3. The prototype plugin transfers more knowledge to users during 3D print preparation compared to the conventional method of 3D print preparation.
4. The prototype plugin offers more guidance than the conventional approach to 3D print preparation.

It is expected that the prototype Objective plugin will be perceived as more guiding and more educative than the conventional approach of 3D print preparation. Control over the model is expected to increase and the control over the printing process is expected to decrease. Moreover, users are expected to be more confident about meeting intended part qualities.

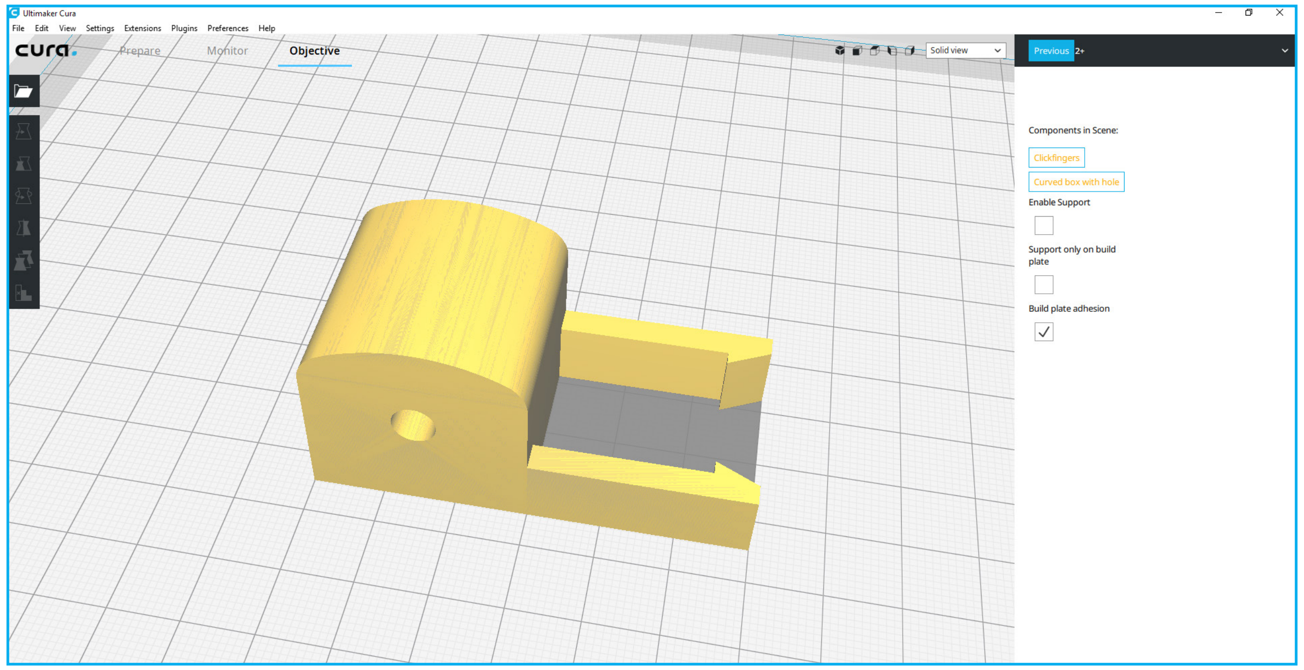
11.2
Method

A small-scale experiment was conducted in order to answer the research questions and validate whether the Objective plugin offers a viable approach to intent-based 3D printing.

Participants
A total of 10 students from the faculty of Industrial Design Engineering at the Delft University of Technology participated in the study. They are separated into two equally sized groups, novices and experts, based on their knowledge of- and experience with- 3D printing.

Materials
The experiment was conducted using a Macbook Pro (15-inch, Late 2011) with a resolution of 1440x900 pixels running on Intel HD Graphics 3000. During the test, Ultimaker Cura version 3.3.1 was used for preparing a single model according to four different objectives using both Cura’s default user interface and the Objective plugin. Prints were prepared for an Ultimaker 2+ using a 0.4 mm nozzle and PLA filament. Before each print preparation, presets for print settings in the user interface are reset and the default print profile is set to the ‘Low Quality - 0.15mm’ profile.

The Objective prototype plugin
Both the Highlighted view and the Focused views of the different components of the model were available to the user. The Highlighted view (Figure 11.1) contains two buttons for selecting components and access to limited support and bed-adhesion settings. The Focused view offers a drop down menu to show different available component profiles.



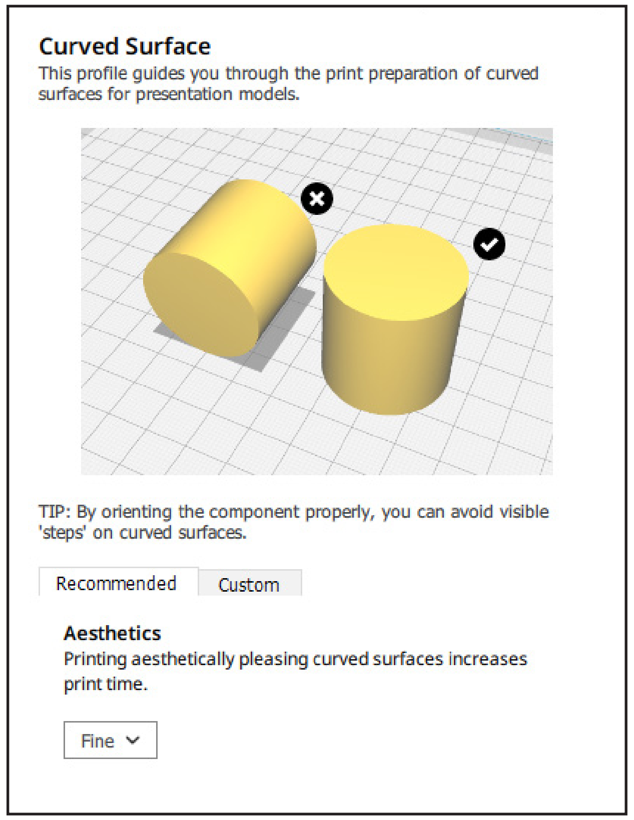
Components in Scene:
Clickfingers
Curved box with hole
Enable Support
☐
Support only on build plate
☐
Build plate adhesion
☑

Figure 11.1 Highlighted view

Component profiles

Four component profiles were available to the user: ‘Accurate Holes’, ‘Curved Surface’, ‘Clickfinger’ and ‘Part Strength’. Each of these component profiles displayed their unique user interface when selected (Figure 11.2-5). These interfaces supplied information to the user about how to successfully prepare a component to achieve intended part qualities.

Each of the component profiles had a ‘Recommended’ and ‘Custom’ tab for manipulating print settings. The Recommended tab of each component profile presented one categorical control and the Custom tab presented multiple print settings to influence process parameters. The controls available in the different component profiles are listed in Table 11.1. The settings available to the user and the presets used for categorical control were based on literature research presented in paragraph 2.4 and expert opinions.



Curved Surface

This profile guides you through the print preparation of curved surfaces for presentation models.

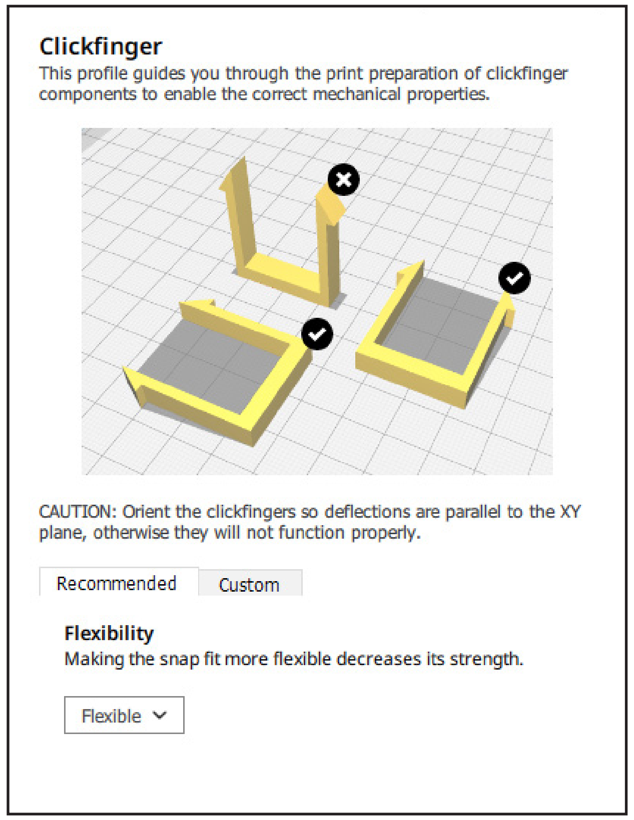
TIP: By orienting the component properly, you can avoid visible 'steps' on curved surfaces.

Aesthetics

Printing aesthetically pleasing curved surfaces increases print time.

Fine

Figure 11.2 Component profile - Curved Surface



Clickfinger

This profile guides you through the print preparation of clickfinger components to enable the correct mechanical properties.

CAUTION: Orient the clickfingers so deflections are parallel to the XY plane, otherwise they will not function properly.

Flexibility

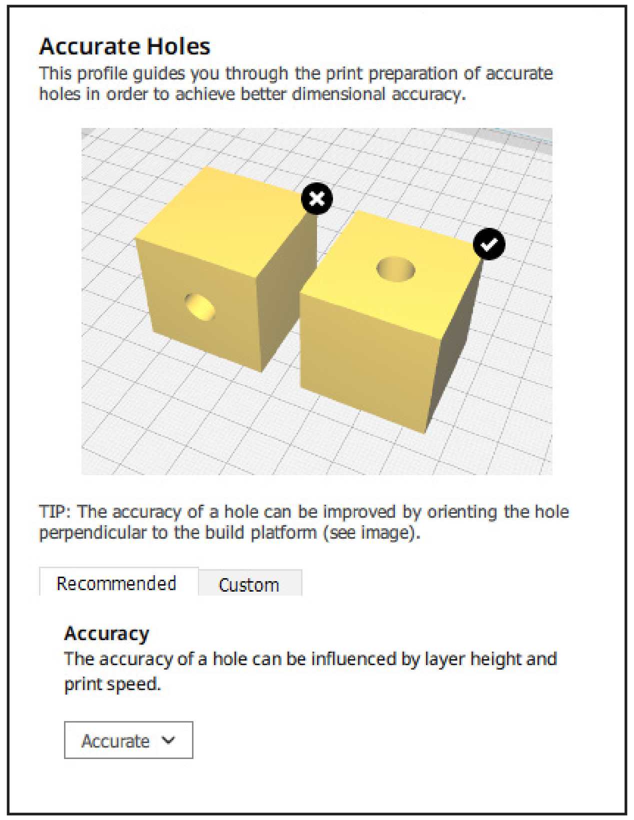
Making the snap fit more flexible decreases its strength.

Flexible

Figure 11.3 Component profile - Cickfinger

Curved Surface		Clickfingers		Accurate Holes		Part Strength	
Recommended		**Recommended**		**Recommended**		**Recommended**	
Low Quality	print speed: 60 infill speed: 100 top thickness: 0.75 bottom thickness: 0.75 profile: Low Quality	Very Flexible	wall line count: 0 infill density: 0 top thickness: 0 top thickness: 0	Normal	print speed: 50 infill speed: 80 top thickness: 0.72 bottom thickness: 0.72 profile: Extra Fine	Normal	wall line count: 1 infill density: 10 print speed: 60 infill speed: 100 top thickness: 0.75 bottom thickness: 0.75 profile: Low Quality
Fine	print speed: 50 infill speed: 50 top thickness: 0.8 bottom thickness: 0.8 profile: Fine	Flexible	wall line count: 1 infill density: 0 top thickness: 0 top thickness: 0	Accurate	print speed: 50 infill speed: 50 top thickness: 0.8 bottom thickness: 0.8 profile: Fine	Strong	wall line count: 2 infill density: 20 print speed: 55 infill speed: 55 top thickness: 0.8 bottom thickness: 0.8 profile: Fine
Extra Fine	print speed: 50 infill speed: 80 top thickness: 0.72 bottom thickness: 0.72 profile: Extra Fine	Stiff	wall line count: 2 infill density: 0 top thickness: 0 top thickness: 0	Very Accurate	print speed: 30 infill speed: 50 top thickness: 0.75 bottom thickness: 0.75 profile: Low Quality	Very Strong	wall line count: 3 infill density: 30 print speed: 50 infill speed: 50 top thickness: 0.72 bottom thickness: 0.72 profile: Extra Fine
Custom		**Custom**		**Custom**		**Custom**	
print speed, infill speed, top thickness, bottom thickness, layer height		wall line count, top thickness, bottom thickness, infill density		top thickness, bottom thickness, print speed, infill speed, layer height		wall line count, top thickness, bottom thickness, infill density, print speed, infill speed, layer height	

Table 11.1 Component profile settings



Accurate Holes

This profile guides you through the print preparation of accurate holes in order to achieve better dimensional accuracy.

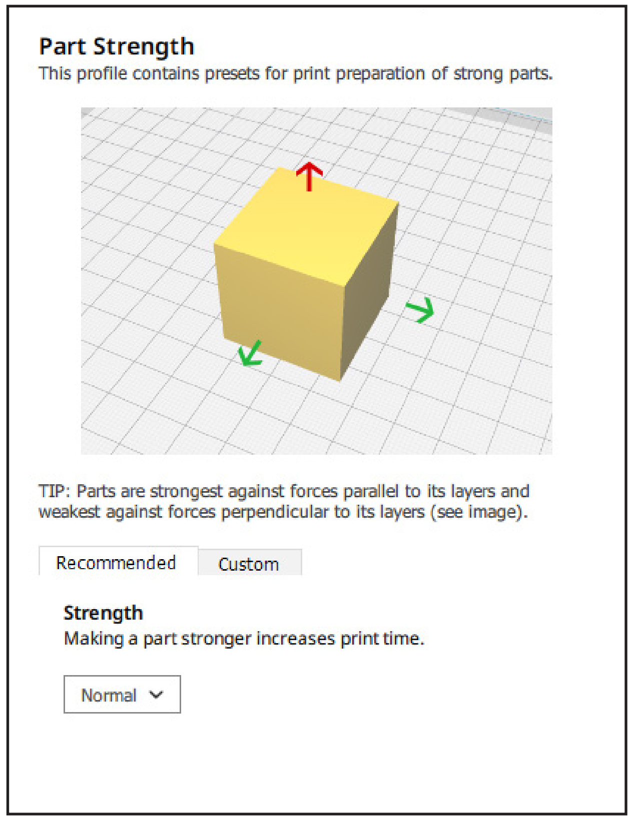
TIP: The accuracy of a hole can be improved by orienting the hole perpendicular to the build platform (see image).

Accuracy

The accuracy of a hole can be influenced by layer height and print speed.

Accurate

Figure 11.4 Component profile - Accurate Holes



Part Strength

This profile contains presets for print preparation of strong parts.

TIP: Parts are strongest against forces parallel to its layers and weakest against forces perpendicular to its layers (see image).

Strength

Making a part stronger increases print time.

Normal

Figure 11.5 Component profile - Part Strength

The model

The 3MF model used for this study is visualized in Figure 11.6. The model used for 3D print preparation has the following features to test how users satisfy different intents:

- **A hole:** The horizontal hole in the model is used for validation of dimensionally accurate parts. To satisfy the intent of printing the hole accurately, the user would have to rotate the model by 90 degrees.
- **A curved surface:** The curved surface is included in order to test how users satisfy the intent of printing an aesthetically pleasing model. In order to print this surface, the user would have to rotate the model by 90 degrees in order to avoid visible discrete layers.
- **Click fingers:** The click fingers are included in order to test how users satisfy the intent of mechanical flexibility. In order to print these, the user does not have to rotate the model, but it is beneficial to use nor infill, nor top- and bottom layers.

The objective plugin splits this model into two individually configurable components: the base with the curved surface and the hole, and the click fingers.

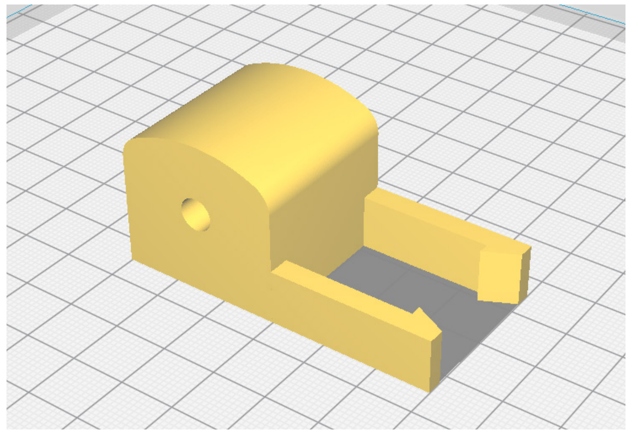


Figure 11.6 The model used for the experiment

Questionnaire

After applying each approach of 3D print preparation, users were asked to give a rating from 1 to 7 for (1) the amount of control over the model, (2) the amount of control over the printing process, (3) the amount of guidance towards meeting their goals, (4) how educative the process was and (5) how confident they were that the result would meet the desired qualities. This was done with a questionnaire that posed the following questions:

- How much control did you feel you had over the model?
- How much control did you feel you had over the printing process?
- How much guidance did you get towards meeting your goals?
- How educative did you find the process?
- How confident are you that the result will meet you expectations and has the desired qualities?

Experimental procedure

Participants completed a total of eight print preparations. The first four print preparations were made using the default user interface in Cura and the remaining four preparations using the prototype plugin. Order was not taken into account during the testing procedure since all participants had experience with print preparations using the default Cura user interface.

The experiment employed both a between subject and a within subject design. The effect of experience with 3D printing was measured using a between subject design and differences in perceived control, knowledge transfer, guidance and confidence in the result between the conventional user interface and the plugin's interface are measured using a within subject design.

First, participants were asked for general information concerning age, education, experience with 3D printing and received education on the topic of preparing 3D prints. The latter two were used to qualify participants as either a beginner or expert user. Next, participants were introduced to the testing procedure, and were told to prepare the supplied 3D model using the two different user interfaces with the following four objectives:

1. "Prepare the model to make the curved area of the model look aesthetically pleasing."
2. "Prepare the model to print the hole dimensionally accurate."
3. "Prepare the model to print the click fingers in a way that they are flexible."
4. "Prepare the model to significantly increase its strength compared to the default print settings."

In addition, they were told to ignore the influences of support materials and assume that possible required support material would not affect the qualities of the printed model. They were also told that temperature control was not taken into account and that layer height could not be controlled in the custom settings of the component profiles, but that if they wanted to change it, they would need to mention it to the researcher, who would reply with whether or not the component profile allowed the layer height to be changed.

After the first four print preparations, the participants filled out the questionnaire for the conventional approach of 3D print preparation. Thereafter they proceeded with preparing four prints using the prototype plugin, followed by filling out the questionnaire again for 3D print preparation using the Objective approach.

Finally, users were asked about their experiences with the prototype plugin and what they would recommend to improve about the user experience.

Data analysis

IBM SPSS 24 is used for data analysis. The following variables were used for the data analysis:

Dependent variables: feeling of control over the model, feeling of control over the process, amount of guidance during print preparation, education, and confidence in the end result
Independent variable: method of print preparation
Grouping variable: experience with 3D printing (beginner or expert)

Firstly, the differences in performance between the two methods of print preparation, as described by the dependent variables, were determined by comparing the mean scores of the dependent variables using Paired Sample T-tests applied across all participants, and across the different user groups (beginners and experts) using the experience as a grouping variable.

Secondly, the differences in performance ratings between beginners and experts were determined by comparing the mean scores of the dependent variables using Independent-Sample T-tests.

11.3
Results

11.3.1. QUANTITATIVE RESULTS

Overall differences in performance

Beginners and experts combined

- No significant difference was found in model control between the two methods of print preparation (t(9) = 1.309, p = 0.223).
- A significant difference was found in process control (mean -2.1) between the two methods of print preparation (t(9) = -3.706, p = 0.005). Participants experience reduced control over the printing process while using the prototype plugin (mean=3.5) compared to while using Cura's print preparation user interface (mean=5.6).
- A significant difference was found in guidance (mean +4.0) between the two methods of print preparation (t(9) = 26.833, p = 0.000). The prototype plugin provides more guidance (mean=6.2) than Cura's print preparation user interface (mean=2.2)
- A significant difference was found in knowledge transfer (mean +3.5) between the two methods of print preparation (t(9) = 6.708, p = 0.000). The prototype plugin is more educative (mean=5.7) compared to the conventional method of print preparation (mean=2.2)
- A near significant difference was found in confidence in the resulting part qualities (mean +0.6) between the two methods of print preparation (t(9) = 2.250, p = 0.051). Participants are likely to feel more confident in the end result while using the prototype plugin (mean=5.3) compared to while using the conventional method of print preparation (mean=4.7)

Beginners

- No significant difference was found in model control between the two methods of print preparation (t(4) = 0.535, p = 0.621).
- A near significant difference was found in process control (mean -1.8) between the two methods of print preparation (t(4) = -2.449, p = 0.070). Beginners experience reduced control over the printing process using the prototype plugin (mean=3.8) compared to the conventional print preparation (mean=5.6)
- A significant difference was found in guidance (mean +4.2) between the two methods of print preparation (t(4) = 21.000, p = 0.000). Beginners find that the prototype plugin provides more guidance (mean=6.6) than conventional print preparation (mean=2.4)
- A significant difference was found in knowledge transfer (mean +3.4) between the two methods of print preparation (t(4) = 3.666, p = 0.021). Beginners find the prototype plugin more educative (mean=5.6) than conventional print preparation (mean=2.2)
- A significant difference was found in confidence in the resulting part qualities (mean +1.2) between the two methods of print preparation (t(4) = 6.000, p = 0.004). Beginners are more confident the resulting part qualities while using the prototype plugin (mean=5.8) than while using the conventional method of print preparation (mean=4.6).

Experts

- No significant difference was found in model control between the two methods of print preparation (t(4) = 1.177, p = 0.305).
- A near significant difference was found in process control (mean -2.4) between the two methods of print preparation (t(4) = -2.588, p = 0.061). Experts experience reduced control over the printing process using the prototype plugin (mean=3.2) compared to the conventional print preparation (mean=5.6)
- A significant difference was found in guidance (mean +3.8) between the two methods of print preparation (t(4) = 19.000, p = 0.000). Experts find that the prototype plugin provides more guidance (mean=5.8) than conventional print preparation (mean=2.0)
- A significant difference was found in knowledge transfer (mean +3.6) between the two methods of print preparation (t(4) = 6.000, p = 0.004). Experts find the prototype plugin more educative (mean=5.8) than conventional print preparation (mean=2.2)
- Absolutely no difference was found in confidence in the resulting part qualities between the two methods of print preparation (t(4) = 0.000, p = 1.000).

Differences between user groups

A couple of significant differences were found between how beginners and experts rate the experience of using the prototype plugin:

- A significant difference was found in guidance while using the prototype plugin (mean +0.8) between the two user groups (t(8) = 3.536, p = 0.008). Beginners perceive more guidance (mean=6.6) than experts (mean=5.8) while using the prototype plugin.
- A significant difference was found in confidence in the resulting part qualities while using the prototype plugin (mean +1.0) between the two user groups (t(8) = 3.536, p = 0.008). Beginners are more confident in the resulting part qualities (mean=5.8) than experts (mean=4.8) while using the prototype plugin.

Discussion of the quantitative results

The quantitative results show that the prototype plugin provides more guidance and education for both beginners and experts. However, this comes at the cost of reduced control over the printing process. Beginners are also significantly more confident that the qualities of the printed part will match their intended qualities. Experts appear to be as confident in the end result while using the prototype plugin as they are while using Cura's print preparation user interface.

Finally, it is notable to mention that beginners are more confident in the end result and experience more guidance than experts. This could possibly be because experts are more doubtful of the proposed settings due to the higher amount of process knowledge they have compared to beginners, and because they are less open to being told what to do due to their over-confidence.

11.3.2. QUALITATIVE RESULTS

During the research, participants made some interesting remarks during and after the study that support conclusions from the analysis phase and provide feedback for further improvement. Next, these remarks are listed and their relevance to the research is explained:

"I know I can look at the layer view, but I just use the infill icon in the recommended view"

This user quote is interesting regarding conclusions from the analogy with 2D printing in chapter 6 that mentioned that more icons could be used to communicate the feedback upon user selections.

"Oh, I did not think about rotating the model before."

This quote was made by an experienced 3D printing user and shows that even experts can benefit from prominent guidance as a reminder.

"Oh, they are already oriented like that."

A user reaction to the hint supplied by the 'Clickfingers' component profile. This quote indicates that the images work well to communicate the desired orientations.

"The conventional approach is not educative at all. You do read the tooltips, but it is not really educative."

This is a comment made by an expert user when filling out the questionnaire on conventional 3D print preparation. The comment supports the conclusions from paragraph 2.3 about the effectiveness of the tooltips in the Cura interface.

"I am tricked into not thinking about the other component because I cannot see the rest of the model."
This quote indicates that it may indeed be beneficial to only show a single component in a Focused view when selecting desired properties of this component, since users may forget about the other parts of the model altogether.

"What is this? Outer or inner wall?"
This quote communicates a previously identified issue with the control of the amount of perimeters when using the infill mesh type in paragraph 10.5.

"There are too few controls when you go to the custom tab. For instance, I can't set different speeds for outer and inner walls."
Similar comments to this quote were made by several 'experts'. The experts understood that the idea was to limit the available process parameters that could be accessed, but wondered whether it would be possible to at least give the option to also adjust more specific settings within the parameters' categories. This would be worthwile to investigate.

"It is still not clear what the settings do."
The current prototype plugin does not present clear indications of how certain qualities of the part and its components are affected by the users' selections. It would be beneficial to add these in the future. Also, since the layer view is not triggered by default, there are no visible changes to the user interface apart from changed print time and material usage metrics. It could be beneficial to trigger layer view automatically in order to show changes in the generated tool paths.

"So this control increases the number of layers. Lower layer heights make the model stronger apparently."
A user that did use the layer view and manipulated the strength control of the 'Part Strength' component profile thus showed signs of the educative experience that the Objective plugin offers to users.

11.4
Conclusions

The posed research questions are answered as follows:

Research Question

How does intent-based 3D printing using the Objective plugin compare to the conventional print process as implemented in Cura?
The quantitative results show that the prototype plugin provides more guidance and education for both beginners and experts at the cost of reduced control over the printing process. Beginners are also significantly more confident that the qualities of the printed part will match their intended qualities. Experts appear to be as confident in the end result while using the prototype plugin as they are while using Cura's print preparation user interface.

Sub-questions

1. How much control is experienced using the two methods of 3D print preparation?
There is no significant difference in control of the model between the Objective plugin and the conventional approach to 3D print preparation offered by Cura, but users do experience a significant loss of control over the process when using the Objective plugin.

2. What method of 3D print preparation is expected to give the best results regarding satisfying the intended part qualities?
Beginners are also significantly more confident that the qualities of the printed part will match their intended qualities. Experts appear to be as confident in the end result while using the prototype plugin as they are while using Cura's print preparation user interface.

3. What is the perceived difference in knowledge transfer, or "educativeness" between the two methods of 3D print preparation?
The Objective plugin is significantly more educative than the conventional approach to 3D print preparation offered by Cura.

4. How does the prototype plugin influence the amount of guidance supplied during 3D print preparation?
The Objective plugin provides significantly more guidance than the conventional approach to 3D print preparation offered by Cura.

11.5

Implications & further research

Implications

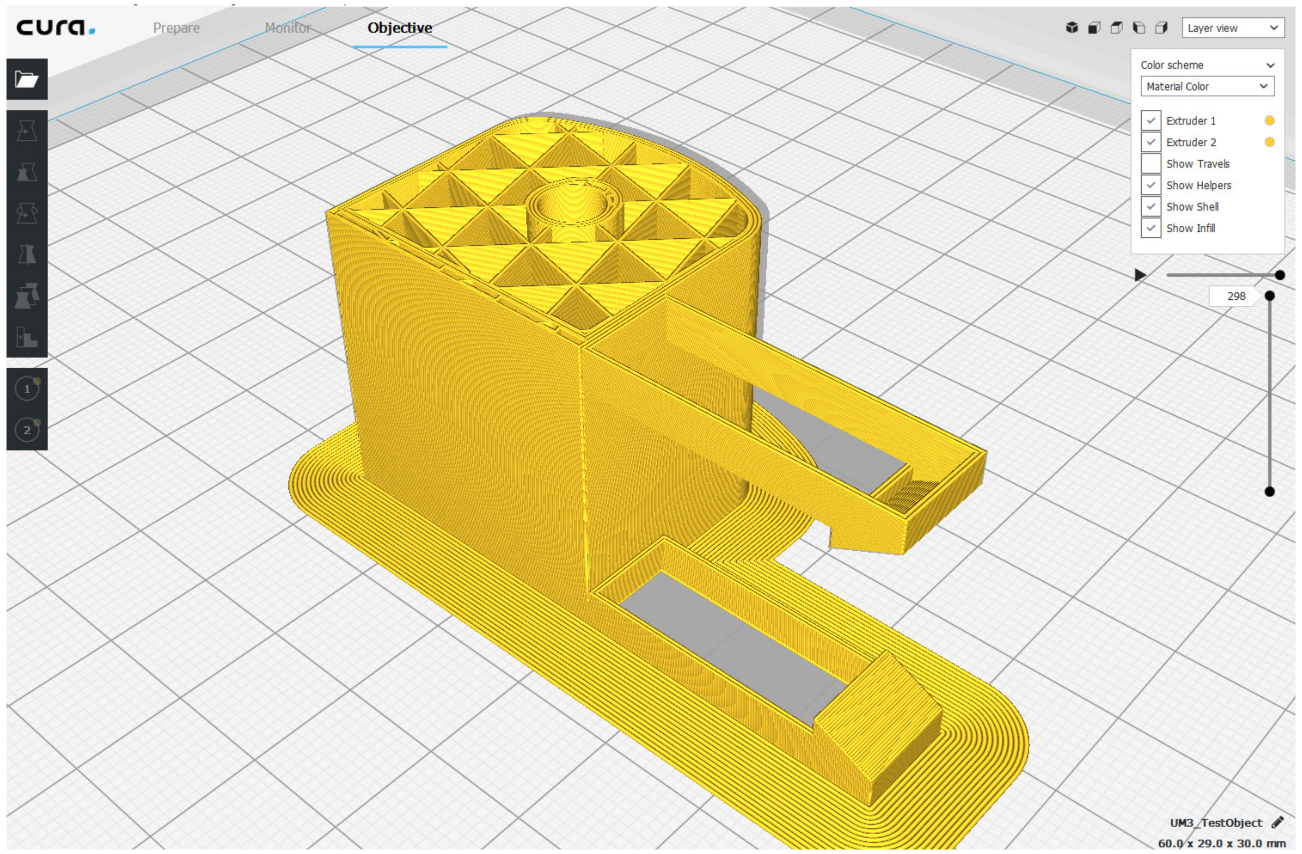
Although the Objective plugin could still be significantly improved and the actual effects of users' sections on the part qualities were not measured, the study shows that the component-based approach using component-profiles meets design criteria set in paragraph 8.3; the Objective plugin provides significantly improved user-education and guidance.

Users are likely to experience a significant loss of control over the printing process when using the Objective plugin. However, this does not seem problematic since beginners are more confident that their intended qualities are achieved, and experts have similar confidence in the end result as they have when they are able to manipulate all kinds of process parameters. In 2D printing users also have confidence in the end result without bothering to change specific process parameters.

Finally, the results of the user test show that the Objective plugin is a promising approach for intent-based 3D printing and that it is worthwhile to continue its development.

Further research

The performed user test focussed on the perceived qualities of the Objective plugin. However, it has not yet been quantified how well the expected qualities such as aesthetics, dimensional accuracy, flexibility and part strength, are met using physical measures of 3D printed models. Further research is recommended for improvement of the Objective plugin and comparing the resulting part qualities that can be achieved while using it with those achieved when using the conventional approach.



Color scheme: Material Color
☑ Extruder 1
☑ Extruder 2
☐ Show Travels
☑ Show Helpers
☑ Show Shell
☑ Show Infill

UM3_TestObject
60.0 x 29.0 x 30.0 mm

Figure 11.7 Component profile settings cause the snap fit to be non-printable because it's desired orientation is not met.

12.

Wrap-up

12.1
Conclusions

This research aims to provide the user with means to better voice his or her intentions throughout the 3DP workflow and to provide the system with means to identify them and present meaningful feedback to the user. Intent is defined as a representation of a combination of actions that an actor or multiple actors may perform in order to achieve a goal.

Throughout the 3D printing workflow, the user is presented with a multitude of action possibilities, or affordances, especially by 3D printing software during print preparation. Significant research has been performed on the influences of these action possibilities on the resulting 3D printed parts. Users are aware that these possibilities, such as changing process parameters and choosing 3D printing hardware and materials, exist and can influence the resulting part qualities. However, it is not clear to them how to take advantage of them.

These users are described as personas: the beginner, the expert and the operator. In this study, the most important users are the beginner and the expert because they are directly involved in print preparation. The beginner desires educative experiences and the expert desires control over the printing process. Both need guidance, but in different ways; the beginner needs encouragement to start applying affordances, whereas the expert needs moderation to compensate his or her overconfidence.

Intentions of users are identified and described in order to design means to achieve intended results. For industrial design students, key descriptives are: function, aesthetics and process. This group is representative of the application of 3D printing in product development; the descriptive may be different in other fields of application.

Product configuration systems used to customize product offerings to consumers offer means to facilitate users' intents. These systems are used as an inspiration for the design of an intent-based 3D printing approach because they share key functionalities with print preparation, such as communicating product offerings, checking completeness and validity, providing real-time information on product qualities and making quotations.

Though this study presents three design concepts, the Objective concept complies best with the users' needs and the design vision: improving the 3D printing workflow by providing an intent-based and model-based 3D printing approach through the delivery of result-driven options, component-level control and incentives.

The Objective concept presents a system architecture that includes 3D printer hardware, software, supportive devices and the Objective plugin. Only the plugin was embodied since it presents the primary intent-based interactions to the user. The Objective plugin uses component profiles from a pre-filtered database - based on intent information included in an imported 3MF file - to control models on a component-level and select 'desired' parameter values to print them. These profiles guide the user towards manipulating process parameters that influence the qualities that the profile represents and educate the user by supplying tips. Subsequently the desired values for process parameters for each of these components are validated and if conflicts occur, dilemmas present the user with meaningful choices that make possible limitations explicit and enable the user to make conscious choices. Finally, the Objective plugin selects suitable 3D printing hardware and materials that help achieve the desired result, rather than have the selected hardware and materials limit the user during print preparation.

Part of the Objective plugin's functionality has been realized as a Cura plugin and has been tested amongst industrial design students. From the user test, it can be concluded that print preparation using component profiles significantly improves user guidance and the educative experience of print preparation. Especially 'beginners' are more confident that their configuration will lead to the desired part qualities. The objective plugin reduces the feeling of control, but even expert users show confidence in the final result. It is plausible that users experience less control because the plugin makes several decisions for them.

Alltogether, within the designed plugin users can better voice their intentions through selecting component profiles. These profiles present meaningful feedback to users that both guides and educates them. Of course the realized plugin has its limitations: it does not use intent information that can be included in the supplied model files, nor does it offer dilemmas to the user. Even though these limitations exist, this study represents a step forward in the journey from process-driven to intent-based 3D printing.

12.2

Recommendations

Due to the scope of this project, both user research and embodiment of the concept were limited. Additionally, the validation tests led to opportunities for improvement of the concept. Based on these limitations and opportunities, this paragraph presents a number of recommendations for further development of the Objective intent-based 3D printing concept:

Recommendations for further development of the Objective concept

- It is recommended to develop a plugin for popular CAD packages for exporting models for intent-based 3D printing using the 3MF file format. This 3MF file should include a mesh of the base models, as well as a mesh for each individually configurable component. In addition to this, the file should include information about the desired qualities of the 3D model and its components.
- It is recommended to further develop the print core storage unit, since it is a low cost interim solution towards industrial, tool changing printers. Benefits of the print core storage unit are that users have a clear insight into the available print cores, all users are familiarized with the print core concept and the Objective plugin can recommend nozzle sizes and nozzle types more effectively. The latter requires the Objective plugin to be able to communicate with Cura Connect during print preparation, which is also recommended as a future development.

Recommendations for component profiles

- It is recommended to include a means for the component profiles to take component dimensions into consideration, since the model's scale can influence the required part qualities. For example, larger click fingers may require more contours to be printed in order to supply the same relative deformation as smaller variants.
- It is recommended to include at least one backup state in each component profile that ensures printability, even if the desired component orientation is not satisfied.
- It is recommended that Ultimaker uses its knowledge from case studies to develop several component profiles for component geometries that are often found in 3D printed objects.
- It is recommended to develop a tool that enables users to create component profiles without the need for programming skills. This will allow users to focus on finding proper parameter combinations, rather than spend time programming the component profile by hand, and will increase the amount and variety of available component profiles.

Recommendations for the user interface

- It is recommended to depart from using a sidebar interface for intent-based 3D printing on a component-level scale. Users indicated a lack of visual relationships between the components and the interface for their selection (Highlighted View), as well as their individual configuration interfaces (Focussed Views). While the objective prototype did not include colour coding for the individual components, which may resolve part of the problem, the visual relationship between selecting components and the interfaces for their individual configuration interfaces could be made more clear by removing these functions from the sidebar. Instead, users should just be able to select the individual components with the mouse to enter their focused view, with the user interface for component configuration displayed close to the model.
- It is recommended to improve the way values for different part qualities are communicated to the user, because users may have different interpretations of values like 'strong', 'very strong', 'stiff' and 'flexible'. Moreover, these may not even be the ultimate qualities that the user desires. For example, a part could require strength for different reasons; sometimes the ultimate goal behind strength is to 'survive an accidental drop', whereas other times the ultimate goal may be to 'be able to stand upon it'. These are examples of how the interface could humanize part quality controls by putting their values into perspective.
- The messages for presenting dilemmas require the user to read the message which is time consuming. Therefore, it is recommended to improve the visual clarity of these dilemmas so users can more quickly make a selection. It may be beneficial to do this in congruence with the previously mentioned statement about the proximity of the interface to the involved models.

Recommendations for further user research

- It is recommended to test how the intents can be mapped using Venn charts in different fields of application of material extrusion 3D printing. This may lead to different principal components that distinguish user intents depending on the field of application.
- It is recommended to test how well dilemmas work for resolving conflicting component parameter values when working with models that have a large amount of components.

12.3
Self-reflection

The learning objectives that I posed in the initial design brief (Appendix D) included improving my user testing skills, broaden my knowledge of architecture design, expanding my knowledge of electronics, acquiring in-depth knowledge of the material extrusion process and to experience working in a professional environment. This paragraph reflects on these learning objectives, as well as the design process and the final result.

Reflection on project process
With this graduation project I was given the chance to work in the additive manufacturing industry. A market that in my view has many exciting challenges in both technology and user interaction. Due to the broad nature of the topic of 'intent', a lot of effort went into the analysis phase. It was during this phase that I discovered many issues that lead to the formation of multiple design opportunities relevant for intent-based 3D printing. It became apparent during the project, that the scope was perhaps still quite big for the time available for this project, which had caused me to invest too much time in the analysis phase. In hindsight, it would have been more beneficial to start the ideation phase of the project sooner, and if needed, return to the analysis phase to answer some of the most critical questions.

This was the first time that I had to plan and execute a large design project by myself. I learned that I am a perfectionist. The work benefits from this through attention to detail and argumentation. The fact that I set a high bar for myself results in spending more time on things than initially planned. Ultimately, this has resulted in a postponed deadline. This experience will help me plan future projects in a more realistic way and set clear boundaries on time-consumption during each phase of the project.

Reflection on design solution
The outcome of the analysis phase meant that the solution became a software product, rather than a hardware product that I was used to design. This posed a lot of challenges, not only in design, but also in prototyping.

Designing a software solution meant the development of the user interaction was the main challenge of the design. This also meant that rather than designing shapes, mechanisms and activators, I was designing user interfaces whilst considering typography, iconography and user interface elements. This meant that the design skills used were more focussed on graphic design-rather than industrial design skills. In the end, I believe I did quite a good job adapting myself to the new situation, and I believe that the visual design complements the Ultimaker brand identity.

Obviously, the development of a software prototype using object-oriented programming was also very different from making a physical prototype. However, past experiences with object oriented programming and programming for the web enabled me to learn Python and Qt quite rapidly. However, since most of this learning took place during the development of the plugin, a number of compromises had to made between the final design and the prototype to test the user interaction. While I was unhappy with these compromises at first, I believe that I managed to do as much as possible given the time, and as an initial pilot for an intent-based printing approach, the prototype supplies a lot of insights for further development.

Experiencing working in a professional environment
Of course, working at the Ultimaker headquarters, and being surrounded by experts in the field of material extrusion 3D printing, helped me gain a lot of in-depth knowledge about the 3D printing process, the market developments and future challenges. Moreover, it was my first time working in a professional environment as a designer. The fact that my workplace was located in departments that were working on different projects than intent-based printing was one of the major challenges. Another challenge was the fact that whilst many individuals within the company are working on the subject of intent-based 3D printing, or projects related to it, there was not yet a clear definition or roadmap for intent-based 3D printing in place at the start of this project. Being present at several meetings and having conversations with colleagues that were also interested in the topic gave me helpful insights, but ultimately, their focus points differed from mine. Discussing the final solution with several colleagues at Ultimaker showed however that the concept aligns with many different focus points of others. Moreover, being present at both hardware and software meetings helped me align my solution with company developments and the market trends.

Broaden knowledge of architecture design
This project allowed me to consider architecture design in two ways: the architecture of the software product, and the system architecture of the software interacting with other hardware products, both in the present and in the near future.

SYSTEM ARCHITECTURE
The designed software needs to communicate with the available hardware in the environment in order to ensure that user intentions can be met in several environments. As mentioned in paragraph 9.3, the software needs to effectively communicate with (future) hardware and software in contexts with a cluster of 3D printers and / or with multiple users. Whilst this architecture is much more simplistic compared to the software architecture, it did allow me to consider a designed product as part of a product family for the first time.

SOFTWARE ARCHITECTURE
As mentioned in this report, the software architecture is heavily based on architectures used in product configuration systems. However, the information that is sent from and to the individual components in this architecture posed a large challenge. Especially coding the final software prototype helped me get a better understanding of how to manage the sharing of data between the different components in the architecture. During this coding experience, I found myself adapting the initially thought out flow of information between the different components of the architecture. Especially the object oriented programming helped me broaden my knowledge of architecture design, since it forced me to consider what objects know about the existence of other objects, and what objects are best suited to carry certain pieces of information to make it available to other objects in the software architecture.

Reflection on user testing
One of my personal goals was to focus more on user testing during the design process. During this graduation project I have successfully conducted four user tests. While I did not focus on the application of research methods derived from the Design for Emotion course, I did manage to improve my user-testing skills. This progression can also be seen throughout this report.

The first user test that I conducted was an explorative study by means of an online survey. This survey was time consuming and reflecting on it I now conclude that this study was better suited for an interview format. While the results of this study were useful for the project process, much of the data

gathered was not useful due to the low amount of participants involved in the study.
I took the shortcomings of the first user test into consideration whilst preparing the second user test. The second user test was also conducted using an online survey but took a lot less time to complete, resulting in more participation. Moreover, the data recovered from this user test was to-the-point and therefore, the results were more useful for the final design.

The third and fourth user test also built upon these past experiences. These user tests, used for validation of the design, were also conducted with a better considered approach. While the approach of the second validation test was slightly altered from the initial validation test, errors in the initial user test were mostly caused by bugs in the prototype software. Even though the user experience validation was limited due to limitations of the software, a lot of valuable insights were gathered that can be built upon in the future.
I have gained a lot of experience in user testing and also benefited from their results, even though I was not able to apply the initially proposed Design for Emotion methods that turned out to be unsuitable for acquiring the intended results.

Closing remarks

At the end of this project, I feel that my efforts have resulted in a lot of learning and a successful end result that I can be proud of. Since the results of this project are limited by the projects' scope, further research needs be conducted on the user experience of the intent-based 3D printing approach, but I feel confident that I made a major contribution to moving from process-driven-, towards intent-based 3D printing approaches.

References

Adobe Acrobat Color settings. (2018). Retrieved from https://helpx.adobe.com/acrobat/using/color-settings.html

An B., Miyashita S., Meeker L., Demaine E.D., Demaine M.L., Rus D., Tolley M.T., Aukes D.M., Wood R.J. (2014). An end-to-end approach to making self-folded 3D surface shapes by uniform heating. In Proceedings of the 2014 IEEE International Conference on Robotics and Automation (ICRA) (pp. 1466-1473). Hong Kong, China: IEEE. doi:10.1109/ICRA.2014.6907045.

An, B., Wu, H., Zhang, T., Yao, L., Tao, Y., Gu, J., Cheng, T., Anthony' Chen, X., Zhang, X., Zhao, W., Do, Y. & Takahashi, S. (2018). Thermorph: Democratizing 4D Printing of Self-Folding Materials and Interfaces. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18). New York, NY, USA: ACM. doi:10.1145/3173574.3173834.

Ang, K. C., Leong, K. F., Chua, C. K., & Chandrasekaran, M. (2006). Investigation of the mechanical properties and porosity relationships in fused deposition modelling-fabricated porous structures. Rapid Prototyping Journal, 12(2), 100-105. doi:10.1108/13552540610652447

Anitha, R., Arunachalam, S., & Radhakrishnan, P. (2001). Critical parameters influencing the quality of prototypes in fused deposition modelling. Journal of Materials Processing Tech, 118(1), 385-388. doi:10.1016/S0924-0136(01)00980-3

ColorPrint - Prusa Printers. (2018). Retrieved from https://www.prusaprinters.org/color-print/

Colour Management - How It Works. (2018). Retrieved from https://www.colourphil.co.uk/rendering_intents.shtml

Cranz, A. (2018). Home 3D Printing 'Just Not There Yet' Admits MakerBot. Gizmodo.com. Retrieved 19 April 2018, from https://gizmodo.com/home-3d-printing-just-not-there-yet-admits-makerbot-1786859285

Crump, S. S. (1992). US 005121329A. Minneapolis, Minnesota: World Intellectual Property Organization

Davidson, D. (1963). Actions, reasons, and causes. The Journal of Philosophy, 60(23), 685-700. doi:10.2307/2023177

Doubrovski, E. L. (2016). Design Methodology for Additive Manufacturing: Supporting Designers in the Exploitation of Additive Manufacturing Affordances. (Doctoral thesis). doi:10.4233/uuid:d4214bb0-5bfd-43fe-af42-01247762b661

Evermann, G. (2014). US 2014/0365209 A1. Cupertino, California: World Intellectual Property Organization

Gartner Says Consumer 3D Printing Is More Than Five Years Away. (2018). Gartner. Retrieved 19 April 2018, from https://www.gartner.com/newsroom/id/2825417

Google. (n.d.). Google Noto Fonts. Retrieved September 24, 2018, from https://www.google.com/get/noto/

Fisher-Wilson, G. (2018). 3D Printing Trends Q1-2018. 3D Hubs Blog. Retrieved 1 May 2018, from https://www.3dhubs.com/blog/3d-printing-trends/ Bratman, M. (1984). Two Faces of Intention. The Philosophical Review, 93(3), 375. http://dx.doi.org/10.2307/2184542

Floor, J.W. (2015). Getting a grip on the Ultimaker 2: Tensile strength of 3D printed PLA: A systematic investigation (master thesis). Delft University of Technology, Delft, The Netherlands.

Gibson, J.J. (1979). The Ecological Approach to Visual Perception. Boston: Houghton Mifflin.

Hairy Lion by _primoz_. (2016). Retrieved from https://www.thingiverse.com/thing:2007221

Horvath, D., Noorani, R., & Mendelson, M. (2007). Improvement of surface roughness on abs 400 polymer using design of experiments (DOE). Materials Science Forum, 561/565, 2389-2392.

Huang, S., Liu, P., Mokasdar, A., & Hou, L. (2013). Additive manufacturing and its societal impact: A literature review. The International Journal of Advanced Manufacturing Technology, 67(5-8), 1191-1203. doi:10.1007/s00170-012-4558-5

ICC profile. (2018). Retrieved from https://en.wikipedia.org/wiki/ICC_profile

Ion, A., Frohnhofen, J., Wall, L., Kovacs, R., Alistar, M., Lindsay, J., Lopes, P., Chen, H.-T., and Baudisch, P. (2016). Metamaterial Mechanisms. In Proceedings of the annual ACM symposium on User Interface Software and Technology (UIST '16) (pp. 529-539). New York, NY, USA: ACM. doi:https://doi.org/10.1145/2984511.2984540.

Ion, A., Wall, L., Kovacs, R. & Baudisch, P. (2017). Digital Mechanical Metamaterials. In Proceedings of the 2017 CHI conference on Human Factors in Computing Systems (CHI '17) (pp. 977-988). New York, NY, USA: ACM. doi:10.1109/ICRA.2014.6907045.

Ion, A., Kovacs, R., Schneider, O. S., Lopes, P., Baudisch, P. (2018). Metamaterial Textures. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18). New York, NY, USA: ACM. doi: https://doi.org/10.1145/3173574.3173910

ISO 17296-2:2015 (2015, January 15). Additive manufacturing — General principles — Part 2: Overview of process categories and feedstock.

International Organization for Standardization

Kagerman, H., (2013). Recommendations for implementing the strategic initiative INDUSTRIE 4.0: securing the future of German manufacturing industry (final report of the Industrie 4.0 Working Group). Frankfurt, Germany: Acatech – National Academy of Science and Engineering.

Kuipers, T., Elkhuizen, W., Verlinden, J., & Doubrovski, E. (2018). Hatching for 3d prints: Line-based halftoning for dual extrusion fused deposition modeling. Computers & Graphics, 74, 23-32. doi:10.1016/j.cag.2018.04.006

Kumar, G., & Regalla, S. (2012). Optimization of support material and build time in fused deposition modeling (FDM). Applied Mechanics and Materials, 110/116, 2245-2251.

Kusiak, A. (2018). Smart manufacturing. International Journal of Production Research, 56(1-2), 508-517. doi:10.1080/00207543.2017.1351644

Laeng, J., Khan, Z.A. & Khu, S.Y. (2006). Optimizing Flexible Behaviour of Bow Prototype Using Taguchi Approach. Journal of Applied Sciences, 6: 622-630.

Lee, B., Abdullah, J., & Khan, Z. (2006). Optimization of rapid prototyping parameters for production of flexible ABS object. Journal of Materials Processing Technology, 169(1), 54.

Lee E. A., (2008). Cyber physical systems: Design challenges. Proceedings of 2008 11th IEEE International Symposium on Object and Component-Oriented Real-time Distributed Computing (ISORC), 363-369

Locker, A. (2016). Ultimaker Interview. [Weblog]. Retrieved 7 March 2016, from https://all3dp.com/ultimakerinterview/

Luciw, W. W., Capps, S. P., Tesler, L. G. (1995). US005390281A. Cupertino, California: World Intellectual Property Organization

Lulz, M. R., Dietz, P. H. (2013). US 2013/0229347 A1. Redmond, Washington: World Intellectual Property Organization

McGrenere, J., and Ho, W. (2000). Affordances: clarifying and evolving a concept. New York, NY: ACM.

Mohamed, O., Masood, S., & Bhowmik, J. (2015). Optimization of fused deposition modeling process parameters: A review of current research and future prospects. Advances in Manufacturing, 3(1), 42-53. doi:10.1007/s40436-014-0097-7

Nancharaiah, T & Ranga Raju, D & Ramachandra Raju, V. (2010). An experimental investigation on surface quality and dimensional accuracy of FDM components. International Journal of Emerging Technologies, 1.

Nancharaiah, T. (2011). Optimization of Process Parameters in FDM Process Using Design of Experiments. International Journal of Emerging Technologies, 2.

Norman, D.A. (1988). The Psychology of Everyday Things. New York: Basic Books.

Research and Development: Motion System and Tool-Changer. (2018). Retrieved from https://e3d-online.com/blog/2018/03/21/tool-changer-q

Riley, J. (2013, March 14). Open Mindsets Link 3D Printing & Internet of Things.

Rittinghouse, J., & Ransome, J. (2010). Cloud computing: Implementation, management, and security. Boca Raton, FL: CRC Press.Computerworld UK. Retrieved from http://www.computerworlduk.com/blogs/internet-of-things/open-mindsets-link-3d-printing--internet-ofthings-3571147/

Roozenburg, N., & Eekels, J. (2003). Productontwerpen, structuur en methoden (2e dr., 3e opl ed.). Utrecht: Lemma.

Paulose, J., Meeussen, A., & Vitelli, V. (2015). Selective buckling via states of self-stress in topological metamaterials. Proceedings of the National Academy of Sciences of the United States of America,112(25), 7639-44. doi:10.1073/pnas.1502939112

Pei, E. (2014). 4D printing – revolution or fad? Assembly Automation, 34(2), 123-127. doi:10.1108/AA-02-2014-014

Pei, E. (2014). 4D printing: Dawn of an emerging technology cycle. Assembly Automation, 34(4), 310-314. doi:10.1108/AA-07-2014-062

Perez, B. (2013, July 22) 3D printing pioneer Scott Crump's kitchen experiment.

South China Morning Post. Retrieved from http://www.scmp.com/business/companies/article/1287961/3d-printing-pioneer-scott-crumpskitchen-experiment

Post processing for FDM printed parts. (2018). Retrieved from https://www.3dhubs.com/knowledge-base/post-processing-fdm-printed-parts

Searle, J. R. (1983). Intentionality: An Essay in the Philosophy of the Mind. Cambridge University Press, New York City, New York.

Setiya, K. (2018). "Intention", The Stanford Encyclopedia of Philosophy (Summer 2015 Edition), Edward N. Zalta (ed.), retrieved on March 28, 2018 from https://plato.stanford.edu/archives/sum2015/entries/intention/

Sood, A.K., Ohdar, R.K., & Mahapatra, S.S. (2009). Improving dimensional accuracy of Fused Deposition Modelling processed part using grey Taguchi method. Materials and Design, 30(1), 4243-4252. doi:10.1016/j.matdes.2009.04.030

Sood, A.K., Ohdar, R.L., & Mahapatra, S.S. (2010). Parametric appraisal of mechanical property of fused deposition modelling processed parts. Materials and Design, 31(10), 287-295. doi:10.1016/j.matdes.2009.06.016

Soto, D. (2013). Know your onions : graphic design. Amsterdam: BIS Publishers.

Super Flowers (drooloop flowers)- customizable by peetersm. (2014). Retrieved from https://www.thingiverse.com/thing:240158

Tempelman, E., Eyben, B., & Shercliff, H. (2014). Manufacturing and design : Understanding the principles of how things are made. Amsterdam: Butterworth-Heinemann.

TheFutur. (2014, May 29). Skool OS CORE Webinar Core Brand Attributes [Video file]. Retrieved from https://www.

youtube.com/watch?v=5l4i3PZucHI&t=1886s

Thrimurthulu, K & Pandey, Pulak & Nallagundla, Venkata Reddy. (2004). Optimum part deposition orientation in fused deposition modeling. International Journal of Machine Tools and Manufacture, 44, 585-594. 10.1016/j.ijmachtools.2003.12.004.

Tibbits, S. (2014). 4D printing: Multi-Material shape change. Architectural Design, 84(1), 116-121. doi:10.1002/ad.1710

Trentin, A., Perin, E., & Forza, C. (2012). Product configurator impact on product quality. International Journal of Production Economics, 135(2), 850-850.

Tseng, M., Jiao, R., & Wang, C. (2010). Design for mass personalization. CIRP Annals, 59(1), 175-178. doi: 10.1016/j.cirp.2010.03.097

Ultimaker. (2016). Ultimaker 3: Installation and user manual. Retrieved on May 3, 2018 from https://ultimaker.com/download/61355/Ultimaker%203%20manual%20%28EN%29.pdf

Ultimaker. (2018a). Ultimaker 3D print cores. Retrieved on May 3, 2018 from https://ultimaker.com/en/products/ultimaker-3-print-cores

Ultimaker. (2018b). Materials. Retrieved on May 7, 2018 from https://ultimaker.com/en/resources/23121-materials

Ultimaker. (2018c). XY offset calibration. Retrieved on May 7, 2018 from https://ultimaker.com/en/resources/23125-xy-offset-calibration

Ultimaker. (2018d). PLA: Fast, safe and reliable 3D printing. Retrieved on May 7, 2018 from https://ultimaker.com/en/products/materials/pla

Ultimaker. (2018e). ABS: 3D print durable and tough prototypes. Retrieved on May 7, 2018 from https://ultimaker.com/en/products/materials/abs

Ultimaker. (2018f). CPE materials: Build tough functional prototypes. Retrieved on May 7, 2018 from https://ultimaker.com/en/products/materials/cpe

Ultimaker. (2018g). PC: Strong, tough, and heat-resistant material. Retrieved on May 7, 2018 from https://ultimaker.com/en/products/materials/pc

Ultimaker. (2018h). Nylon: 3D print strong, durable prototypes. Retrieved on May 7, 2018 from https://ultimaker.com/en/products/materials/nylon

Ultimaker. (2018i). TPU 95A: Print durable and flexible parts. Retrieved on May 7, 2018 from https://ultimaker.com/en/products/materials/tpu-95a

Ultimaker. (2018j). PP: Durable and lightweight 3D printing material. Retrieved on May 7, 2018 from https://ultimaker.com/en/products/materials/pp

Ultimaker. (2018k). PVA: Water-soluble support for complex models. Retrieved on May 7, 2018 from https://ultimaker.com/en/products/materials/pva

Ultimaker. (2018l). Breakaway support material for dual extrusion. Retrieved on May 7, 2018 from https://ultimaker.com/en/products/materials/breakaway

Ultimaker (n.d.). Professional 3D printing made accessible. Retrieved September 24, 2018 from https://ultimaker.com

Van Boeijen, A.G.C., Daalhuizen, J.J., Zijlstra, J.J.M., Van der Schoor, R.S.A. (2013). Delft Design Guide. Amsterdam: BIS Publishers

Van der Kruit, M. (2014). De maakbare wereld van 3D-printen - Opensource printen met Ultimaker. Tweakers.net. Retrieved from http://tweakers.net/video/8840/de-maakbare-wereld-van-3d-printen-ultimaker.Html

Velleman, J., & Bratman, M. (1991). Intention, Plans, and Practical Reason. The Philosophical Review, 100(2), 277. http://dx.doi.org/10.2307/2185304

Wang, Che-Chung & Lin, Ta-Wei & Hu, Shr-Shiung. (2007). Optimizing the rapid prototyping process by integrating the Taguchi method with the Gray relational analysis. Rapid Prototyping Journal - RAPID PROTOTYPING J. 13. 304-315. 10.1108/13552540710824814.

Wijnia, S. (2015) PlugnMake – NLmakertour – Ultimaker full interview. [video] Retrieved on April 11, 2018 from https://www.youtube.com/watch?v=Y6jmvWlQOWs&feature=youtu.be

Wohlers Associates (2017). Wohlers Report 2017: 3D Printing and Additive Manufacturing State of the Industry Annual Worldwide Progress Report. Fort Collins, Colorado, USA: Wohlers Associates, Inc. ISBN 978-0-9913332-3-3

Zaleski, A. (2018). The 3D Printing Revolution That Wasn't. WIRED. Retrieved 19 April 2018, from https://www.wired.com/2016/12/the-3d-printing-revolution-that-wasnt/

Zhang, J., & Peng, A. (2012). Process-Parameter optimization for fused deposition modeling based on taguchi method. Advanced Materials Research, 538, 444-447.

Zhang, Y., Zhang, G., Wang, J., Sun, S., Si, S., & Yang, T. (2015). Real-time information capturing and integration framework of the internet of manufacturing things. International Journal Of Computer Integrated Manufacturing, 28(8), 811-822. http://dx.doi.org/10.1080/0951192x.2014.900874

Zheng P., Xu X., Yu S., Liu C. (2017). Personalized product configuration framework in an adaptable open architecture product platform. Journal of Manufacturing Systems, 43, 422-435. doi:10.1016/j.jmsy.2017.03.010

Zheng, P., Wang, H., Sang, Z., Zhong, R., Liu, Y., Liu, C., Xu, X. (2018). Smart manufacturing systems for industry 4.0: Conceptual framework, scenarios, and future perspectives. Frontiers of Mechanical Engineering, 13(2), 137-150. doi:10.1007/s11465-018-0499-5