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Analysis of Slicing-Tools for Fused Deposition Modeling 3D-Printers and comparison of different printers

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Kurzfassung

Der Begriff 3D-Drucker bezieht sich auf Geräte der additiven Fertigungstechnologie, die Gegenstände durch sequentielle Schichtung erstellen. Objekte, die additiv gefertigt werden, können überall im Produktlebenszyklus, von Rapid Prototyping über die Kleinserienproduktion bis zur Vollproduktion auftreten. Zusätzlich zur eigentlichen Hardware werden Werkzeuge bzw. Anwendungen wie beispielsweise „Slicing Tools"und Post-Produktions Anpassungen, sowie Vorgehensmodelle und Test- und Prüfszenarien nötig.

Mit Hilfe dieser Slicing Tools ist es möglich digitale 3D-Modell in Druckanweisungen für 3D-Drucker zu konvertieren. Das allgemeine Vorgehen ist hierbei das folgende: das Modell wird in horizontale Scheiben (Schichten) geschnitten, aus welchen dann Fahrbahnen erzeugt werden, ähnlich der Fräsbahnen im traditionellen CNC-Umfeld, um diese mit Material (meist Kunststoff) zu füllen. Anschließend wird häufig auch die Menge des zu extrudierenden Materials (Kosten- und Zeitabschätzung) berechnet.

Diese Fachstudie hat zum Ziel auf verschiedenen 3D-Druckern einen Vergleich der zur Verfügung stehenden Slicing Tools unter verschiedenen Aspekten mittels verschiedener Konfigurationen durchzuführen. Die drei Hauptaufgaben dieser Fachstudie sind: 1. Das Sammeln von Methoden und Werkzeugen zur Beurteilung der Druckergebnisse, 2. Die Analyse der zur Verfügung stehenden Slicing Tools und 3D-Drucker mittels geeigneter Tests und Vergleiche und 3. Das Bewerten der Slicing Tools auf Basis der Untersuchungen.

Abstract

The term 3D printer refers to machines capable of additive manufacturing, which means creating objects by sequential layering. Additive manufactured objects can be used in the whole product life cycle, from rapid prototyping through small series production up to full production. In addition to the hardware itself it is necessary to use tools and applications like "slicing tools", post-production adjustments, process models and testing and verifying scenarios.

With slicing tools it is possible to convert digital 3D models into printing instructions for 3D printers. The general approach is: The model is cut into horizontal slices which are then used to create extrusion paths similar to milling paths in the traditional CNC field, which are then being filled with material, mostly plastic material. Commonly the amount of extruded material is being calculated subsequently (price and time estimate).

The goal of this study is to compare available slicing tools on multiple 3D printers under defined aspects using different configurations. The main contributions of this study are: 1. Collecting methods and tools to judge print results, 2. Analysis of the available slicing tools and 3D printers with appropriate tests and comparisons and 3. Evaluating the slicing tools using the analysis as solid foundation.

Contents

Chapter 1

Introduction

1.1 Motivation

3D printing offers a lot of opportunities to build and create things simply by scanning or modeling the required object in order to print them. The print quality mainly depends on the used printer and slicing tool. To achieve a good print quality a good slicing tool configuration is essential, but the configuration may vary according to the used 3D printer and slicing tool. The task of the slicing tool is to convert a 3D mesh into a set of toolpaths that can be understood by the printer. The produced set of toolpaths is henceforth denoted as G-Code file and basically is a text file consisting of computer numerical control instructions (CNC) for the extrusion nozzle. G-Codes are parts of CNC instructions beginning with the letter G and are specified in *ISO 6983*. It contains all commands necessary to control a 3D printer [1]. In the following listing 1.1 you can see a simple example of a G-Code with two lines of computer numerical control instructions.

Listing 1.1: Simple G-Code Example

```
N010 G00 X50 Y100
N020 G01 X20 Y20 Z30
```

G00 stands for rapid positioning and *G01* stands for linear interpolation. *X*, *Y* and *Z* are the appropriate coordinates of the respective instructions.

Slicing tools generally have various options for converting the 3D mesh into G-Code such that slicing tool can produce different G-Codes which might influence the quality of the printed object. Hence, it is possible to get different G-Codes for the same model and the 3D printer prints the same model with major or minor differences.

The result of a 3D print also depends on the configuration of the 3D printer itself. For example the used filament size of an extruder is a configuration option of the 3D printer. Different filament sizes can have an impact on the quality of printed results.

Given all these options it is not self-evident to print models with a high quality. In this study we want to examine the impact of the various options on the quality of the printed object.

1.2 Goals

The goals of this study are as follows:

Goal 1: Without applying reproducible and useful metrics a discussion on quality differences of 3D printed objects is impossible. We want to provide consistent and useful metrics in order to formalize the quality impacts we want to examine.
Goal 2: We want to provide a framework to measure and improve the overall quality of 3D printed objects by providing a set of benchmark models.
Goal 3: We want to apply our framework with our metrics to state of the art slicing tools in order to evaluate the framework and the slicing tools.

In order to achieve these goals we would like to answer the following questions during our study. The questions are intended to capture different aspects of the slicing tools and their respective impact on the quality.

What is the influence of different slicing techniques on...
Question 1: ... the quality of the surface of the printed object? Different fill patterns, extrusion speeds and extrusion paths can be used to improve the quality of the surface.
Question 2: ... the quality of overhangs and bridges (chapter 4.1.2)? The extrusion speed, a fan cooling and fill patterns can have a huge influence on the quality of overhangs and bridges.
Question 3: ... the overall precision of the printed shapes and objects? A perfect print has the exact same specifications as its corresponding virtual 3D model.
Question 4: ... the stability of the model? A printed model should not fall apart when being touched or moved.
Question 5: ... the general printability of a 3D model? A high print bed adhesion can for example ensure that the model does not move while printing.

1.3 Document structure

In chapter 2 we will give an overview of the technology and terminology used for 3D printing. We will continue by going into detail of the slicing tools in chapter 3. The foundations of our measurements and the approach we use to analyze the models is outlined in chapter 4. In chapter 5 we will examine the reproducibility of 3D printers and compare two FDM printers against each other. The influence of the slicing tools on the quality of the printed object will be examined in detail in chapter 6 while chapter 7 compares the different slicing tools concerning usability. Chapter 8 will summarize our findings and provide ideas for future work.

Chapter 2

Technology

In this section we explain the printing technology and tool chain we used in our tests. For all our tests we used the technology fused deposition modeling (FDM).

2.1 FDM Printing

Fused deposition modeling is a 3D printing technology where molten plastic beads are extruded layer by layer. FDMs most prominent use is Rapid Prototying [2].
A plastic filament is molten and pushed through a thin extrusion nozzle. The extrusion amount can be controlled with the feed rate. The extrusion head is usually positioned in two dimensions, while extruding one layer. When a layer is finished the head is moved upwards relative to the model and the next layer is printed.
All in all a three dimensional plastic model is built by controlling the extrusion head position, controlling the feed rate and moving upwards layer by layer.

FDM was developed and established by Stratasys in the late 1980 [10]. In 2005 the RepRap project was started[1]. It developed low cost do it yourself FDM printers that can even reproduce parts of themselves. Various commercial printers based on the RepRap printers were brought to market (eg. Makerbot[2] and Ultimaker[3]). These relatively cheap printers, compared to industrial printers, and the RepRap project made low cost 3D printing possible for the first time.

Normal FDM printing has some limitations. It is not possible to print full colored models, usually the models are printed in a single color. In our tests we also only used single color printing.
One other limitation is the inability to print large overhangs. Overhangs can only be printed when printing support structures that prevent the extruded material from hanging down. We focused on the slicing process itself, therefor we did not use support structures in our tests.

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[1] http://reprap.org
[2] http://www.makerbot.com
[3] https://www.ultimaker.com

2.2 Used Printers

In this section the 3D printers will be presented.

1. RepRap-Mendel, iteration 2[4]
    - ◇ Self made with parts from a kit
    - ◇ Simple design of threaded rods and printed plastic parts
    - ◇ Dual-extruder for $3.0mm$ plastic filament
    - ◇ $0.5mm$ Nozzle
    - ◇ Heated print bed
    - ◇ Fan for print cooling
2. Makerbot Replicator 2X[5]
    - ◇ Commercial printer
    - ◇ Robust aluminum housing
    - ◇ Dual-extruder for $1.75mm$ plastic filament
    - ◇ $0.4mm$ Nozzle
    - ◇ Heated print bed

2.3 Used Material

For all tests we used ABS (Acrylonitrile butadiene styrene) thermoplastic filament. Most of the tests are printed with red filament, some with black and gray filament. All used material was originate from the same manufacturer.

When printing with the RepRap-Mendel printer we used $3mm$ filament, for printing with the Makerbot Replicator 2X we used $1.75mm$ filament.

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[4] http://reprap.org/wiki/Prusa_Mendel_%28iteration_2%29

[5] http://www.makerbot.com

2.4 File Formats

Usually there are two file formats used for printing:

- ◇ The input file representing the three dimensional model to be print
- ◇ The printer control file in a numerical control (NC) programming language containing the tool path information.

The three dimensional model files are usually in the *STL* format (STereoLithography)[6] - a popular exchange format for simple, uncolored models and mesh based models. This format is supported by most of the 3D CAD and modeling applications.
The printers of the RepRap project or based on it use *G-Code* files as printer control files. Theses files tell the printers what to do.

2.5 Slicing

The normal workflow of 3D printing is:

- ◇ Creating the three dimensional model to print and exporting it (eg. to *STL*)
- ◇ Calculating the printer control based on the three dimensional model and exporting (eg. to *G-Code*)
- ◇ Printing, based on the control file

The process of calculating the printer control based on the model file is called *slicing*. This is done by separate tools, so called *slicing tools*.
There are various slicing tools with different advantages and disadvantages. The quality of the slicing can have a huge impact on the printing result.
This case study's main focus is to show the difference between slicing tools and how they affect the printing quality.

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[6] StereoLithography Interface Specification, 3D Systems, Inc., July 1988

Chapter 3

Slicing Tools

Slicing tools calculate the printer tool paths from given three dimensional mesh based models. In our tests the input of the slicing tools is always a *STL* file, the output is always a *G-Code* file.

As explained in Chapter 2, FDM printing is done layer by layer. This means that the printer tool paths are also layer based.
Therefor the slicing tools must slice the given three-dimensional model into two-dimensional layers. This can be a difficult task, especially when there are problems with the model, for example the model is not manifold. Some slicing tools can deal with this and there are external tools to repair models. We will not elaborate the handling of erroneous models in this case study.

For each layer the slicing tool has to generate a two-dimensional tool path for the printer. This includes the movement on two axis and the feed rate of the extruder.
Here is the main task of a slicing tool- optimal paths and extrusion speeds. If these are calculated badly the print can be not precise, unstable or even completely failed.
A good slicing tool does not only calculate the layers separately but also look into the layers above and below. Especially when dealing with overhangs and complicated structures the slicing tools can optimize a lot this way.
A good slicing tool also does not simply lay paths over the model. The tool paths must be generated in a way that the printed model is printable, stable and similar to the original shape. To achieve this the slicing tools must intelligently generate perimeters paths and infill paths.

In the end a good slicing tool is not enough. All slicing tools have more or less configuration parameters. A good operator must know the 3D printer he is printing on and which settings (speed, temperature, layer) to use for a specific model to get the best results. In the section slicing tool configuration 3.5 we explain the settings we used for our tests.
All settings are optimized for our main printer, a RepRap-Mendel printer. Our print results are depending on this printer and can be different on other printers.

3.1 Available Slicing-Tools

After researching we found the following slicing tools to be the most popular slicing solutions (as of May 2014):

- ◇ Cura, 14.03 (open source project by Ultimaker)[1]
- ◇ KISSlicer, 1.1.0.14 (commercial project)[2]
- ◇ Skeinforge, Release 50 (open source project)[3]
- ◇ Slic3r, 1.0.0 RC3 (open source project)[4]
- ◇ RepSnapper, 2.2.0 b3 (open source project)[5]
- ◇ Miracle-Grue/Makerware, 2.4.1.62 (freeware project by Makerbot)[6]

3.2 Selection Criteria

From the available slicing tools we found we used the following criteria for selecting the slicing tools to investigate in this study:

- ◇ Reliability: The slicing tool must be able to handle all our test models.
- ◇ G-Code compatibility: The G-Code must be compatible with the RepRap firmware so that we can print it with our RepRap Mendel printer
- ◇ Configurable: To get comparable results with different slicing tools all of them must offer specific configuration properties. The properties "print temperature", "print bed temperature", "layer thickness", "fill density", "print speed" and "minimum layer print time" must be configurable.
  In every test we configured all slicing tools with the same configuration values.

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[1] http://software.ultimaker.com/
[2] http://kisslicer.com/
[3] http://fabmetheus.crsndoo.com/
[4] http://slic3r.org/
[5] https://github.com/timschmidt/repsnapper
[6] http://www.makerbot.com/makerware

3.3 Excluded Slicing Tools

Based on our selection criteria we had to exclude 2 slicing tools

Miracle-Grue/Makerware

The G-Code generated with Miracle-Grue was not compatible with our RepRap-Mendel printer. Therefor we had to exclude it because there was no way to compare the results with the other slicing tools on our RepRap printer.

RepSnapper

RepSnapper was excluded because it did not work reliably. When slicing the model *DragonsEgg* the slicer crashed every time. When slicing the model *TextTest* not all parts of the model were sliced.
RepSnapper is in an early development beta state. The latest binary release 2.2.0-b3 (as of May 2014) is not stable enough for a comparison.

3.4 Selected Slicing Tools

Within the scope of this work 4 slicing-tools will be analyzed and described: *Cura*, *KISSlicer*, *Skeinforge* and *Slic3r*.

Cura

Cura the open source software developed by Ultimaker includes everything to prepare a 3D file for printing and slicing it. It's available on *Linux*, *Mac* and *Windows*. Multiple industry-standard files like *STL (stereolithography)*, *OBJ (Wavefront 3D file)*, *DAE (Digital Asset Exchange)* and *AMF (Additive Manufacturing File)* can be used.
There are 4 simple standard profiles included. Cura has a user-friendly graphical interface, the buttons with main functionalities are well-arranged and mostly labeled.
Cura is presented in detail in Section **7.1**.

KISSlicer

KISSlicer is a closed source slicing tool, there is a free version and which has all the features needed for a single-head machine which can be extended to PRO version with support of multi-head machines and multi-model printing. It generates G-Code from *STL (stereolithography)* files.
KISSlicer is available on *FreeBSD*, *Linux*, *Mac* and *Windows*. You can use KISSlicer in different languages. KISSlicer has a gray theme with orange-colored buttons.
KISSlicer is presented in detail in Section **7.1**.

Skeinforge

Skeinforge is an free open source program. It is composed of Python scripts which generates G-Code instructions of a 3D model for RepRap. Skeinforge supports the file formats *STL, GTS (GNU Triangulated Surfaces)*, *OBJ*, *SVG (Scalable Vector Graphics)*, *XML (Extensible Markup Language)*, *GCODE* and *BFB (G-Code in the Bits From Bytes format)*.
Skeinforge is more complicated to install and the user interface is less intuitive compared to other slicing tools. The better way to install Skeinforge is installing it with other host software which includes Skeinforge.
Skeinforge is presented in detail in Section **7.1**.

Slic3r

Slic3r converts *STL (stereolithography)*, *OBJ (Wavefront 3D file)* and *AMF* 3D models into G-Code instructions.
It's available on *Linux*, *Mac* and *Windows*. Additionally Slic3r can be used from the command-line tool. The GUI version provides a G-Code and model visualization as well as profiles and a configuration wizard. Slic3r is also integrated in various printer host softwares.
Slic3r is presented in detail in Section **7.1**.

3.5 Slicing Tool Configuration

For all tests we used mostly the same slicing tool configurations to get reproducible and comparable results.

Speed Settings

◇ Travel Speed - Speed of the extrusion head when not printing:
$150\frac{mm}{s}$

◇ Bottom Layer Speed - Speed of the first layer on the print bed:
$20\frac{mm}{s}$

◇ Shell/Perimeter Speed - Speed of the perimeters:
$30\frac{mm}{s}$

◇ Infill Speed - Speed for internal fill:
$45\frac{mm}{s}$

◇ Minimal Layer Time - Minimum time for each layer to print. Gives the layer enough time to cool, prevents warping. Speed is reduced per layer if necessary.
$20s$

Fill Settings

◇ Fill density - Percentage of fill density for inner beads
20%

◇ Fill pattern - Pattern how to do infill
Rectilinear

Temperature Settings

The temperature settings are the recommended settings for our RepRap Mendel printer for printing ABS. For other printers different settings might be better.

◇ Printing temperature - Temperature of the plastic extruder
250° C

◇ Bed temperature - Temperature of the print bed
110° C

Layer Settings

For the tests we used three different layer thicknesses. For every model we tried out different layer thicknesses and chose the best setting. These settings are optimized for printing on a RepRap-Mendel printer.

- ◇ 0.2*mm* for solid models with no complicated structures. Gives a smoother surface.
- ◇ 0.3*mm* for models with complicated and thin structures. Gives more robust results and less errors.
- ◇ 0.4*mm* for models with overhang. The surface is rougher but there are less errors at overhangs.

Support Structures

In all tests we printed without support structures. Our main goal was to look how good the slicing tools can handle difficulties without support.
In general support structures decrease the print quality (arrears, imprints) so the results are best if a slicing tool succeeds printing a model without support structures.
All test models are printed without raft (layers below the model to improve printbed adhesion). With good slicing tool configurations and a well adjusted printer there is no need for a raft which also decreases the print quality.

Advanced Settings

Most of the other setting values were set to the slicing tools default values. This might affect the printing results. In some cases it would be possible to set settings to the same values but we decided to keep the default values.
Anyway it is the slicers responsibility to offer good default settings so that normal users don't have to change the default settings.
We enabled retraction (pulling back the filament when traveling) for all slicing tools.

Chapter 4

Foundations

In this section we present the criteria and metrics we use to compare slicing tools and printed results.

4.1 Quality Impacts

The main goal when printing is to obtain a physical object that has the same geometry as the virtual 3D model. Thus it is of high importance that the printed object is a very close representation of the 3D model. Models may have a complicated geometry that makes it difficult for the printer to distribute the filament equally which leads to small deviations in the printed result. Furthermore physical constraints like gravitation can have a huge impact while printing on bridges and overhangs. In this section we will describe the deviations that commonly occurred throughout our study and how we quantified them.

4.1.1 Surface Roughness

Every printed object consists of multiple surfaces that may either be flat or follow a specific form. As extruding limits the printer to place tube-like structures as seen in figure 4.1 on the printed object it is not self-evident that the printed surface will be smooth. In fact, if the model surface is angular the printed surface tends to be like a staircase.

Figure 4.1: Tube-like structures forming the actual object

If the model surface is flat we can distinguish between vertical surfaces and horizontal surfaces. The quality of horizontal surfaces mainly depends on two factors. First, a huge impact is made by the slicing tool by deciding on how many filament rows to extrude within the surface. If there is too much filament within the surface the surface might become uneven, if there is too little filament within the surface the gaps between each filament row become large and thus the surface roughness increases. The second factor is the precision of the 3D printer. Slight deviations of the ideal extrusion line of less than $0.1mm$ in lower layers can have an impact on upper layers as the filament could be more dense in a certain area and thus upper layers would be slightly higher in the same area. If one layer is slightly higher it might also occur that the extruding nozzle smears the filament while printing in the higher area.

As it is difficult to quantify the precision of the used 3D printer with the tools that we have available we will not focus much on the surface roughness throughout this study but will refer to the surface roughness in textual form if our findings are visually and haptically different.

4.1.2 Overhangs and Bridges

We define overhangs as extruded material without supporting structures right underneath. Overhangs are generally attached to existing structures (we have not printed using support material in this study) of the layer below so the overhanging material keeps in place. Overhangs are generally used to progressively print sloped surfaces in vertical direction.
A bridge is an overhang that connects two points within the same layer where there is no material in between the points in the layer below. Bridges are usually printed by speeding up the nozzle while extruding in midair.

In both cases a fan cooling can be used to speed up solidification in order to lessen the unwanted impact of gravity. We define the precision of overhangs and bridges by measuring the maximum deviation of the specific overhang or bridge to its ideal shape in the direction of the surface normal.

4.1.3 Plastic Remains

During printing the nozzle often changes between extrusion mode and move mode. It is of high importance that the nozzle stops extruding in the correct location as stopping too soon might leave some details of the model missing and stopping too late might lead to unwanted plastic remains on the surface of the model. Plastic remains can also arise when the nozzle smears non-solid filament that has already been extruded.

In order to determine the size of plastic remains we measure the maximum deviation of the plastic remain compared to the ideal shape of the model in the direction of the surface normal. As plastic remains are usually relatively small we also take into account that plastic remains can manually be removed after the print has finished. We define a plastic remain as removable if it could be removed residue-free from the printed object with the help of a sharp scalpel. If the diameter of the plastic remain is too large removing the plastic remain would leave a white dot on the surface of the model. The removal is then not residue-free which we hence do not define as removable.

4.1.4 Strength

Parts printed with fused deposition modeling can have problems with strength. Along the layer- or bead-joints the parts are much weaker. This is the main strength problem of FDM printed parts.
How weak the parts are along the joints depends on different factors. The main factors are print temperature and print speed.
The hotter the parts are printed the better the layers and beads join. When printing colder the layer below is already cooled down and there is nearly no welding. Printing to hot also can cause problems with warping or burned material so there is a temperature limit.
When printing too fast the plastic can't lay down properly and the strength also suffers. However a problem with printing to slow is that the material cools down and the issues with printing to cold mentioned above occur.
In our tests we mostly printed with $25\frac{mm}{s}$ print speed and 250° C extruder temperature.

4.1.5 Print bed Adhesion

One important requirement for a successful print is the print bed adhesion. If the adhesion is not good enough the print tends to warp or even come off the print bed.
The adhesion depends on various factors: Print bed temperature, printed material and the printer toolpaths. For all our adhesion tests we used the material ABS and a print bed temperature of 110° C (measured with an infrared thermometer).
For a test series all prints to compare are printed with the same model, a print bed with the same temperature and at the same position on the print bed.

4.2 Metrics

In order to quantify and compare the quality impacts mentioned in the last section we have developed some metrics. This section will give an overview on what metrics we used and how me measured them.

4.2.1 Metric for Deviations

A very frequently used metric is the metric for deviations between the printed model and the original model. In general there can either be too much material or too little material in the printed model. In case there is too much material we measure the maximum length of the deviation in the direction of the surface normal. In case there is too little material we measure the minimum perpendicular distance of the whole.
We measured the deviations with a caliper precise on $0.01mm$, as shown in figure **4.2**.

Abbreviation	Name	Description
(R)	Removable	It is possible to residue-free remove the deviation
(D: $< 0.2mm$)	Very small deviation	$< 0.2mm$ deviation in the surface normal
(D: $0.2 - 1mm$)	Small deviation	$0.2mm - 1.0mm$ deviation in the surface normal
(D: $1 - 2mm$)	Rough deviation	$1.0mm - 2.0mm$ deviation in the surface normal
(D: $\geq 2mm$)	Very rough deviation	$\geq 2mm$ deviation in the surface normal
(M: $< 1mm$)	Very small gap	$< 1.0mm$ missing material in the shortest perpendicular
(M: $1 - 2mm$)	Small gap	$1.0 - 2.0mm$ missing material in the shortest perpendicular
(M: $2 - 8mm$)	Large gap	$2.0 - 8.0mm$ missing material in the shortest perpendicular
(M: $\geq 8mm$)	Very large gap	$\geq 8.0mm$ missing material in the shortest perpendicular
(C)	Catastrophe	The printed model does not correspond to the original model in any way.

Table 4.1: Metric used for measuring model deviations

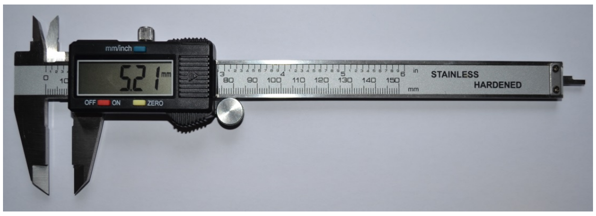

Figure 4.2: Caliper used for measuring the deviations

4.2.2 Metric for Text Quality

In our tests for printing text we printed lines with decreasing letter size for testing how small letters the slicing tools can render. We rated all lines separately.
For each line use the following ratings:

Name	Description
Perfect	All letters are readable and close to the original shape
Readable	All letters are readable but not all have the original shape
Partially readable	Up to four letters are not properly readable
Not readable	More than four letters are not readable

Table 4.2: Metric used for measuring text print quality

4.2.3 Metric for Stability

For measuring the stability of printed parts we measured the toughness (fracture and tensile toughness) in kilograms. We used the best result as reference for rating the other results. The exact test setting is described in the test description in **6.8**.

4.2.4 Metric for Print Bed Adhesion

We also measured the adhesion to the print bed in Newton (N). Therefor we pulled off a freshly printed model from the print bed and measured the necessary force with a spring scale.
The necessary force to pull the printed model off represents the adhesion of the model.

Figure 4.3: Spring scale for measuring print bed adhesion

4.3 G-Code Viewer

In order to analyze the various G-Codes produced throughout this study we have extended the gCodeViewer[1] by Alex Ustyantsev for our needs. We have added the possibility to examine multiple G-Codes at once and have adapted the color scale to color the G-Code paths as a function of the actual extrusion width in millimeters per second. The color legend is thus the same for all G-Codes throughout this study and is shown in figure 4.4.

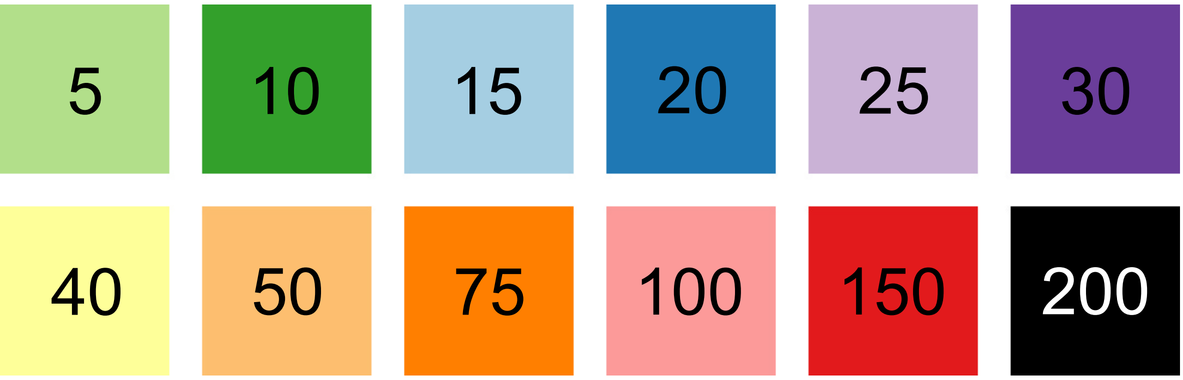

Figure 4.4: Color legend of all G-Code figures in this study. Extrusion speeds are measured in $\frac{mm}{s}$

Figure 4.5 provides a screenshot the user interface of the G-Code viewer. The sample screenshot has two different G-Codes of the same model loaded, but each model has been sliced with different slicing tools. As zooming and moving gestures are synchronized between both model views, it is very easy to visually examine the models for differences.

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[1] `http://gcode.ws/`

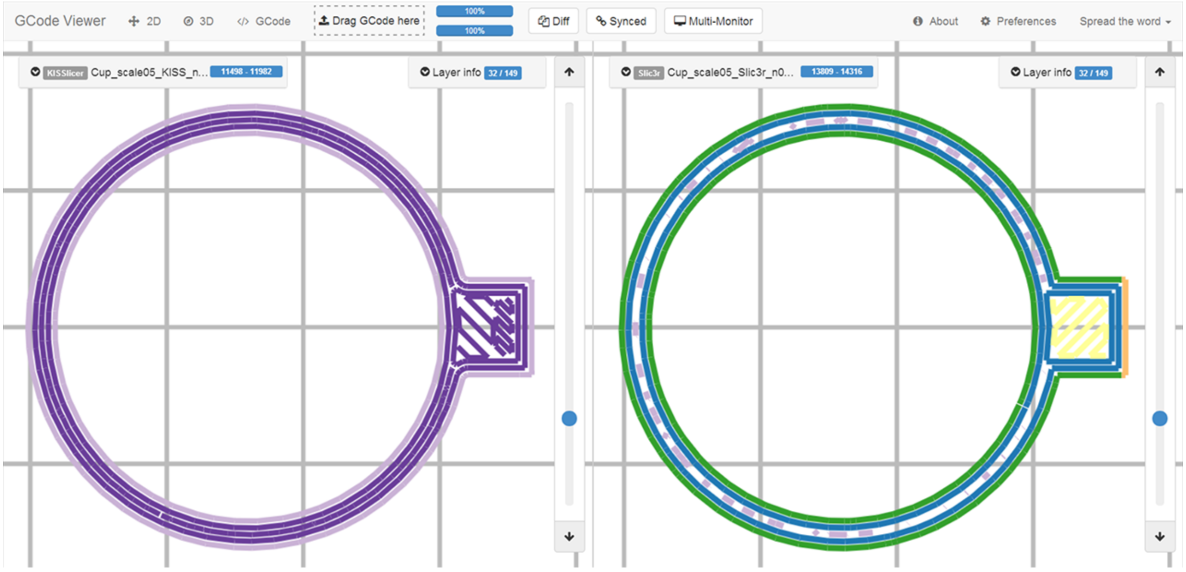


Figure 4.5: Screenshot of the user interface of the adapted G-Code viewer

4.4 Threats to Validity

4.4.1 FDM Printer

For this study we have made several assumptions concerning the used FDM printers. First, we assume that the print results are consistent. That means that if we reprint the same model on the same printer we receive the same 3D objects with deviations generally being smaller than $0.2mm$. We also expect that failures at a certain point in the model will occur again if we reprint the model. In order to minimize this risk we conducted a reproducibility test (see chapter 5) which confirmed our assumption for one model. We also assume that the wear and tear of the printer while printing the models for this study has not a big influence on the quality. In order to assure this we have continually made sure that the printer does not shake while printing and that all screws are fastened tightly. In addition to that we have not printed other models in between that were not involved in this study with the used printers. We have not exchanged the nozzle during the tests, but instead had two nozzles of different sizes mounted from the beginning on to test the influence of the nozzle size. We have not modified the fan cooling throughout the study.

Next to the printer a major threat to validity is the actual filament used, as the specific chemical attributes of the filament may have an influence on the printed results. In order to reduce this risk we have used a single filament spool with red ABS to print all red models throughout this study before changing the spool to a single black spool of ABS to print the black models. The filament spools originate from the same vendor.

4.4.2 G-Code Viewer

As the viewer does not reuse any program code of 3D printers, the viewer itself might be a risk for this study as an inaccurate visualization would lead to wrong conclusions. In order to minimize this risk, we have not manipulated the way the G-Codes are being rendered on the screen during the extension of the viewer. As the original gCodeViewer is an open source project, many people have used the software and have reported many bugs they found. During our study there were no unresolved issues in the issue tracker of the gCodeViewer that could have potentially influenced the visualization. In addition to that we have compared the visualization with all models printed throughout this study and found no difference between the visualized G-Code and the actual extrusion paths. Thus, we assume that the G-Code being displayed accurately represents the extrusion moves of the nozzle while printing.

Chapter 5

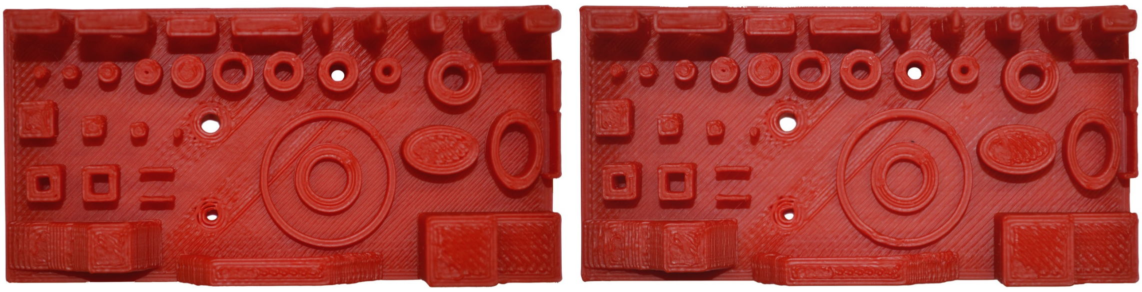
Reproducibility and Printer Comparison

An important requirement for accurate, reproducible and significant test results is the reproducibility of the results.
In this section we present the reproducibility under stable conditions as well as with an other printer.

5.1 Reproducibility

For testing how reproducible the test results are we printed one of our test models twice under same conditions - same model, same G-Code, same printer and same temperature (25° C).
As test model we used the model Precision Test **6.6**. This model has various difficulties like thin structures, holes and bridges. We used KISSlicer for slicing and the same settings like in **6.6**.

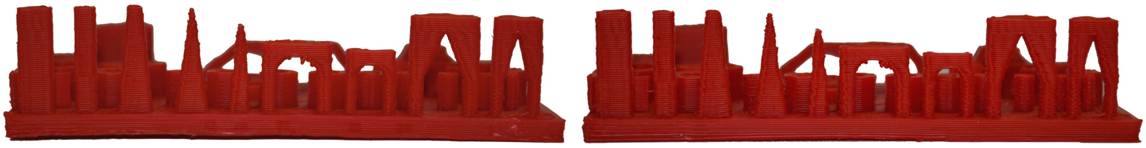
The following pictures show both prints printed under same conditions in direct comparison (same G-Code, 25° C).
All pictures show, that nearly all prominent errors are very similar - the stripes on the surface and the porous surface around the smaller whole in **5.1**, the frayed archway and the incomplete barbs in **5.2** and the dips at the bridge in **5.3**.



(1) Print 1

(2) Print 2

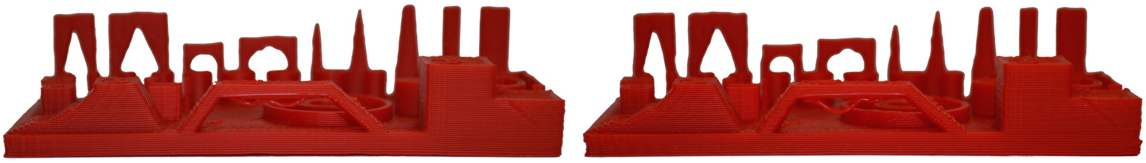
Figure 5.1: The Precision Test model printed twice under same conditions - Top



(1) Print 1

(2) Print 2

Figure 5.2: The Precision Test model printed twice under same conditions - Side 1



(1) Print 1

(2) Print 2

Figure 5.3: The Precision Test model printed twice under same conditions - Side 2

We also measured the deviations of the two prints - deviations from the original model and difference between both prints.

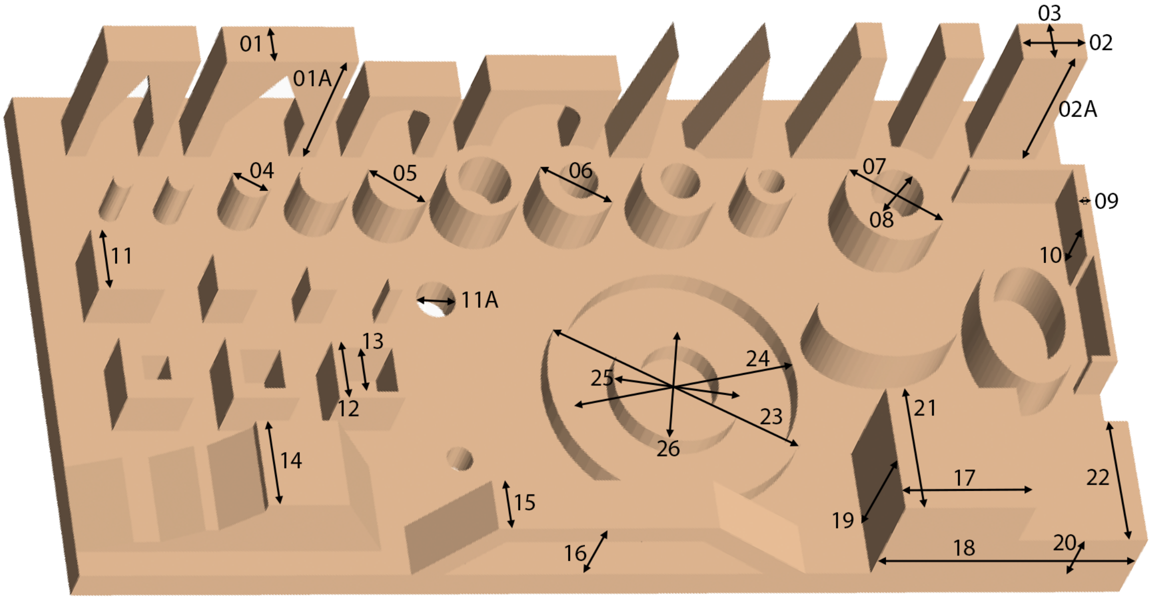
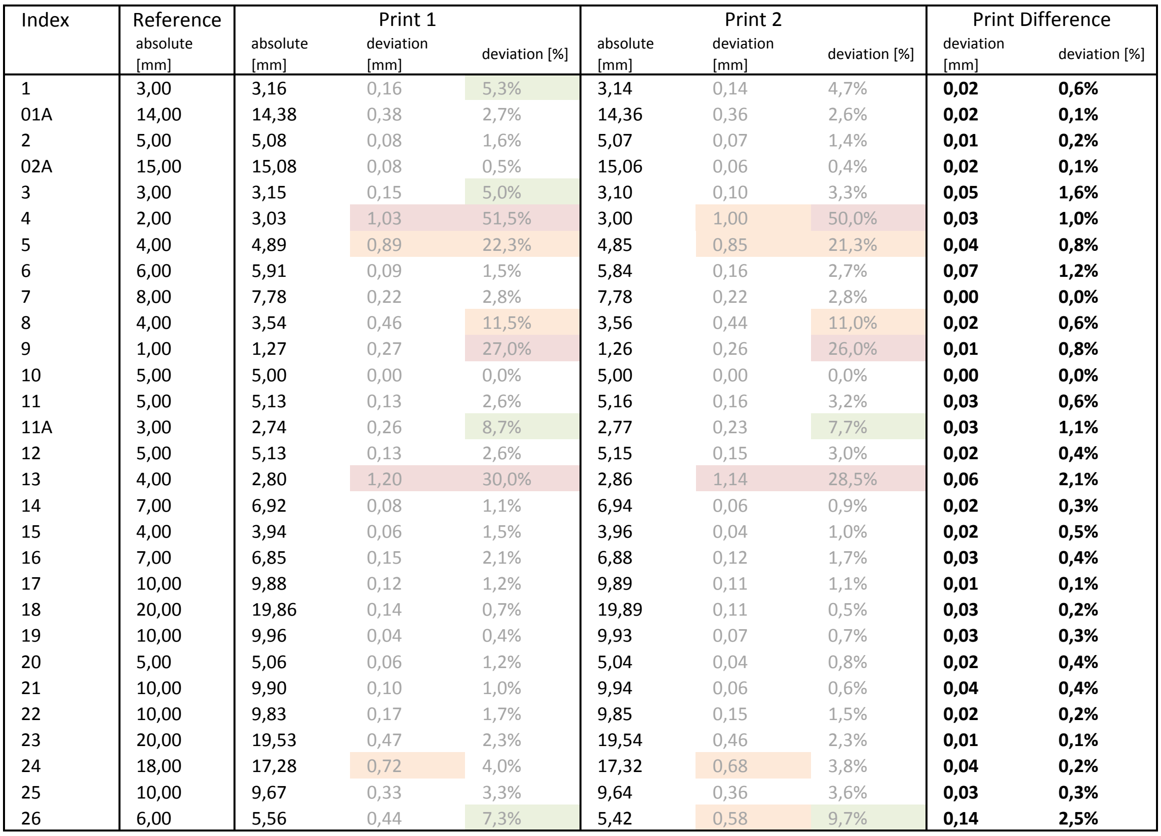


Figure 5.4: Locations measured with the caliper



Index	Reference	Print 1			Print 2			Print Difference	
	absolute [mm]	absolute [mm]	deviation [mm]	deviation [%]	absolute [mm]	deviation [mm]	deviation [%]	deviation [mm]	deviation [%]
1	3,00	3,16	0,16	5,3%	3,14	0,14	4,7%	**0,02**	**0,6%**
01A	14,00	14,38	0,38	2,7%	14,36	0,36	2,6%	**0,02**	**0,1%**
2	5,00	5,08	0,08	1,6%	5,07	0,07	1,4%	**0,01**	**0,2%**
02A	15,00	15,08	0,08	0,5%	15,06	0,06	0,4%	**0,02**	**0,1%**
3	3,00	3,15	0,15	5,0%	3,10	0,10	3,3%	**0,05**	**1,6%**
4	2,00	3,03	1,03	51,5%	3,00	1,00	50,0%	**0,03**	**1,0%**
5	4,00	4,89	0,89	22,3%	4,85	0,85	21,3%	**0,04**	**0,8%**
6	6,00	5,91	0,09	1,5%	5,84	0,16	2,7%	**0,07**	**1,2%**
7	8,00	7,78	0,22	2,8%	7,78	0,22	2,8%	**0,00**	**0,0%**
8	4,00	3,54	0,46	11,5%	3,56	0,44	11,0%	**0,02**	**0,6%**
9	1,00	1,27	0,27	27,0%	1,26	0,26	26,0%	**0,01**	**0,8%**
10	5,00	5,00	0,00	0,0%	5,00	0,00	0,0%	**0,00**	**0,0%**
11	5,00	5,13	0,13	2,6%	5,16	0,16	3,2%	**0,03**	**0,6%**
11A	3,00	2,74	0,26	8,7%	2,77	0,23	7,7%	**0,03**	**1,1%**
12	5,00	5,13	0,13	2,6%	5,15	0,15	3,0%	**0,02**	**0,4%**
13	4,00	2,80	1,20	30,0%	2,86	1,14	28,5%	**0,06**	**2,1%**
14	7,00	6,92	0,08	1,1%	6,94	0,06	0,9%	**0,02**	**0,3%**
15	4,00	3,94	0,06	1,5%	3,96	0,04	1,0%	**0,02**	**0,5%**
16	7,00	6,85	0,15	2,1%	6,88	0,12	1,7%	**0,03**	**0,4%**
17	10,00	9,88	0,12	1,2%	9,89	0,11	1,1%	**0,01**	**0,1%**
18	20,00	19,86	0,14	0,7%	19,89	0,11	0,5%	**0,03**	**0,2%**
19	10,00	9,96	0,04	0,4%	9,93	0,07	0,7%	**0,03**	**0,3%**
20	5,00	5,06	0,06	1,2%	5,04	0,04	0,8%	**0,02**	**0,4%**
21	10,00	9,90	0,10	1,0%	9,94	0,06	0,6%	**0,04**	**0,4%**
22	10,00	9,83	0,17	1,7%	9,85	0,15	1,5%	**0,02**	**0,2%**
23	20,00	19,53	0,47	2,3%	19,54	0,46	2,3%	**0,01**	**0,1%**
24	18,00	17,28	0,72	4,0%	17,32	0,68	3,8%	**0,04**	**0,2%**
25	10,00	9,67	0,33	3,3%	9,64	0,36	3,6%	**0,03**	**0,3%**
26	6,00	5,56	0,44	7,3%	5,42	0,58	9,7%	**0,14**	**2,5%**

Figure 5.5: Results of the measurement of Precision Test with the caliper

5.2 Printer Comparison

For testing how reproducible the test results are on other printers we printed the same model (Precision Test **6.6**) on our second test printer - the Makerbot Replicator 2X.
Unfortunately we had to take a different slicing tool for the Makerbot - Miracle-Grue/Makerware. The G-Code we produced with the other slicing tools was not compatible with the Makerbot.
This had an effect on the slicing result. This comparison is only for showing that theses models can be printed on other printers successfully too.

Both printers can print the given G-Code without bigger errors. There are missing parts but this was caused by the slicing tools.
The Makerbot has less and smaller errors but there are surfaces with missing infill. The RepRap has smoother surfaces especially the flat surfaces.

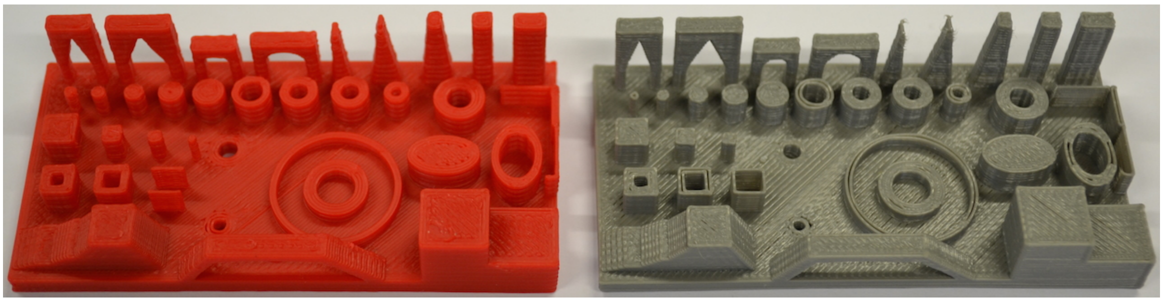


Figure 5.6: The Precision Test model printed with RepRap (red) and Makerbot (gray)

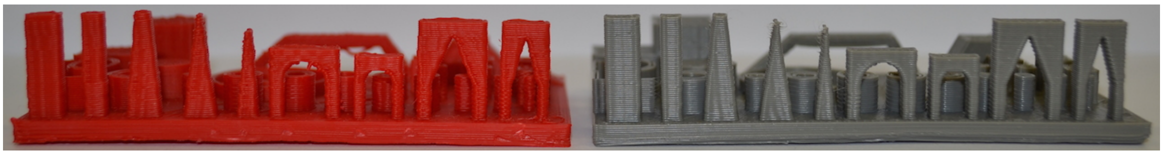


Figure 5.7: The Precision Test model printed with RepRap (red) and Makerbot (gray)

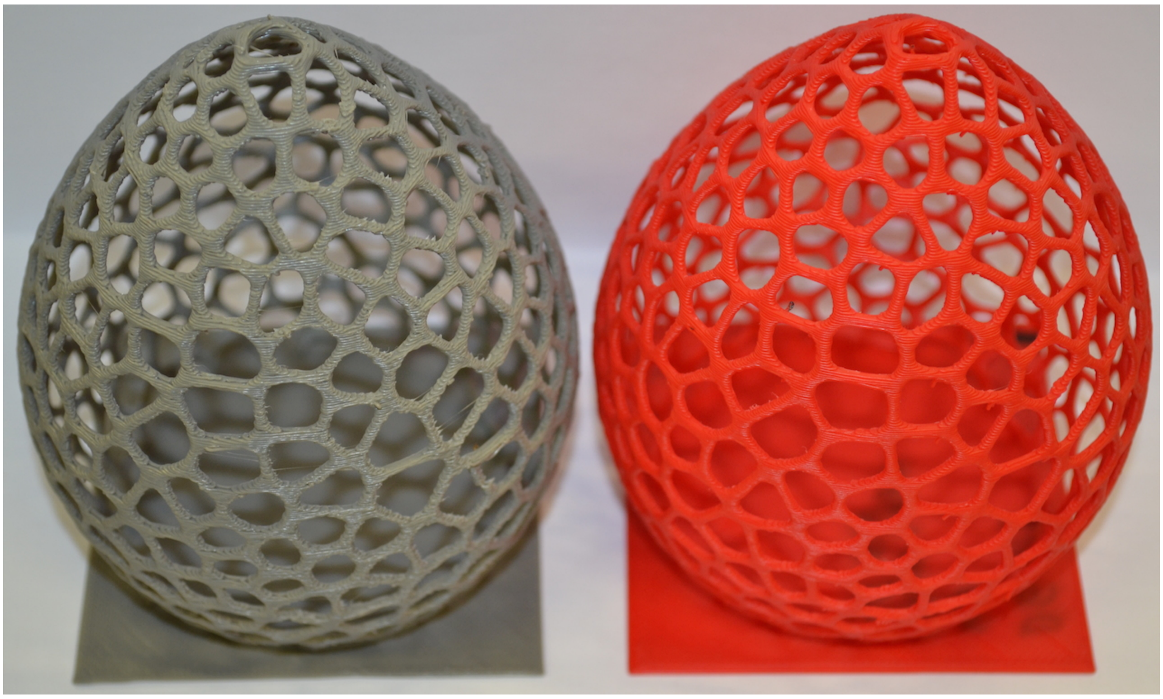


Figure 5.8: The Dragon's Egg model printed with RepRap (red) and Makerbot (gray)

Chapter 6

Evaluation of Slicing tools

In this chapter we will evaluate the different slicing tools using various test models. For each test model we will first give a brief overview of what the models looks like, why we chose each model and where the difficult parts of the model are. Afterwards, we will analyze the different slicing tools with a certain comparison goal for each model and examine the root cause of the detected difficulties.

6.1 Dragon's Egg

The Dragon's Egg [11] has the form of an egg and is hollow. The surface of the Dragon's Egg has many round and oval holes. As seen in figure 6.1 the Dragon's Egg seems to be difficult to print due to the large number of overhangs and its fragile structure.

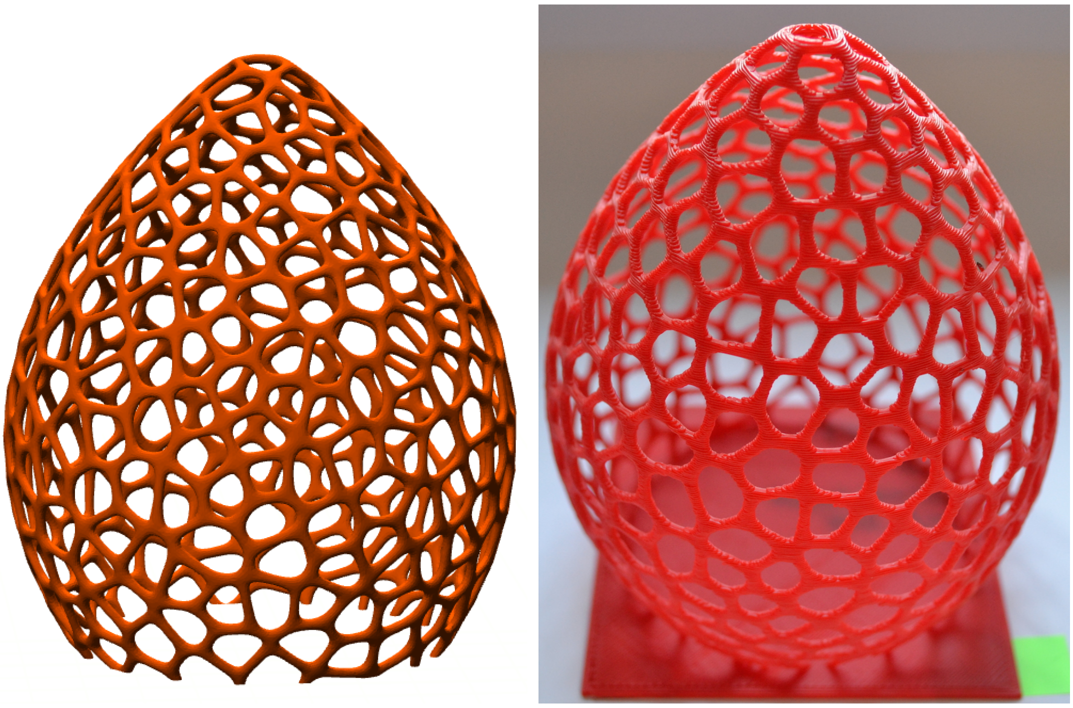
We chose the Dragon's Egg as first model for this study because the slicers we examined produced very different G-Codes and we wanted to examine whether these differences actually have an impact on the print result. The main differences in the G-Codes are found in the fill patterns for the different columns of the egg shell.

6.1.1 Comparison of slicing tools using Dragon's Egg

We have printed the Dragon's Egg with different slicing tools using the same settings in order to compare the impact of the different slicing tools. The most important settings used and a brief overview of the observations of the printed models are listed in table 6.1.

Observed Difficulties:

The surface of the printed models differ very much. KISSlicer (Figure 6.2-2) has a very smooth and constant surface where all pillars of the egg shell have the same width in each layer. The surface of the model sliced with Slic3r (Figure 6.2-4)) is a bit rougher than the one produced by KISSlicer as the width of the pillars begin to differ slightly between the layers. Skeinforge (Figure 6.2-3) and Cura (Figure 6.2-1) have produced a very rough and padded surface due to the fact that the width of the pillars tend to be wider compared to the other two slicing tools.



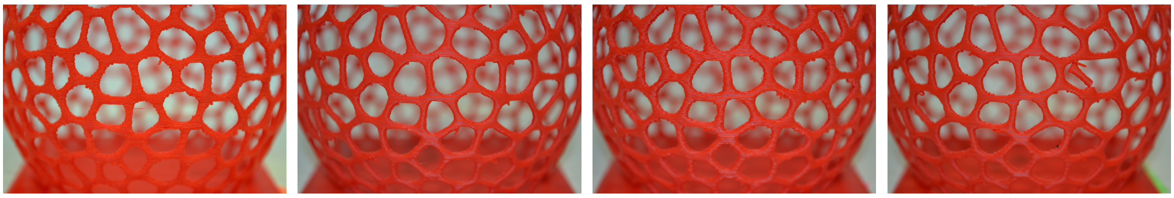
(1) Dragon's Egg- model **(2)** Dragon's Egg- front view

Figure 6.1: Comparison of 3D model and a printed version of the Dragon's Egg

Slicing tool	Nozzle	Layer Thickness	Observations
Cura	$0.5mm$	$0.3mm$	small protruding filaments (R)
KISSlicer	$0.5mm$	$0.3mm$	small protruding filaments (R), smooth surface
Skeinforge	$0.5mm$	$0.3mm$	small protruding filaments (R), small overhangs (D: $0.2 - 1mm$)
Slic3r	$0.5mm$	$0.3mm$	many protruding filaments (R), two larger failures (M: $2 - 8mm$)

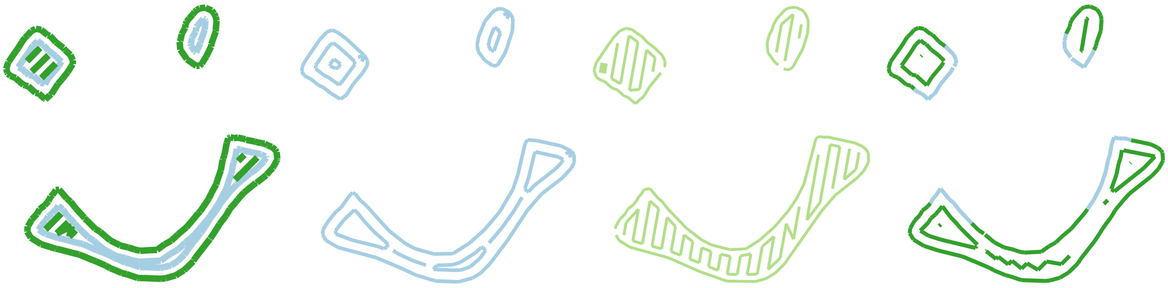
Table 6.1: Observed results for different slicing tools for Dragon's Egg

Considering the differences of the G-Codes of the various slicing tools it is easy to spot that the G-Codes do in fact have a huge influence on the printed result. Figures 6.2-5-6.2-8 each show a layer of the pillars that are visible within figures 6.2-1-6.2-4. The roughness of the surface of a printed result directly correlates with the fill pattern used within the pillars. KISSlicer does not extrude very much material inside a pillar whereas Skeinforge and Cura decide to put very much material inside. The G-Codes visible in figures 6.2-9-6.2-12 are taken from the top of the Dragon's Egg model and underline the consistent difference between the G-Code fill patterns used by the different slicing tools.



(1) Cura **(2)** KISSlicer **(3)** Skeinforge **(4)** Slic3r

(5) Cura layer 129 **(6)** KISSlicer layer 129 **(7)** Skeinforge layer 129 **(8)** Slic3r layer 129



(9) Cura layer 326 **(10)** KISSlicer layer 326 **(11)** Skeinforge layer 326 **(12)** Slic3r layer 326

Figure 6.2: Erroneous parts of the Dragon's Egg with different slicing tools

Another major difference between the slicing tools are the removable protruding filaments. Cura, KISSlicer and Skeinforge have a lot of small dots that mostly point inwards. Slic3r has long protruding strings that point inwards, outwards and sidewards.

6.1.2 Comparison of layer thickness and nozzle size using Dragon's Egg

In order to determine the impact of the layer thickness and the nozzle size we printed the Dragon's Egg using 4 different settings with the KISSlicer as shown in Table 6.2.

Slicing tool	Nozzle	Layer Thickness	Observations
KISSlicer	$0.3mm$	$0.2mm$	very smooth and clean surface
KISSlicer	$0.5mm$	$0.2mm$	very smooth surface, minor irregularities in thickness
KISSlicer	$0.5mm$	$0.3mm$	smooth surface
KISSlicer	$0.5mm$	$0.4mm$	rough surface

Table 6.2: Observed results for different layer thicknesses for Dragon's Egg

6.2 Overhang Test

The next model is the Overhang Test model [12]. As the name suggests, this is a good model to test overhangs with different degrees. This model has overhangs with degrees of 15°, 20°, 25°, 30°, 35°, 40° and 45°. It has two overhangs with the same degree. One overhang is supported by walls and the other overhang is unsupported.

We chose this model for this study as we experienced different qualities of the printed overhangs in the Dragon's Egg. This model allows us to correlate the quality of the overhangs with the different decisions the slicing tools made.

The overhangs supported by the wall can be printed using the bridging technique. The unsupported overhangs are printed by continuously exceeding the edges of the layer below with filament. In any case it is very important that the extruded filament remains in the place it was extruded to regardless of whether it is printed in midair or not. This can be achieved by using a cooling fan to cool down the extruded filament. Thus for this model we also examined the influence a cooling fan has on the quality of the printed model.

6.2.1 Comparison of Overhang Test with and without fan cooling

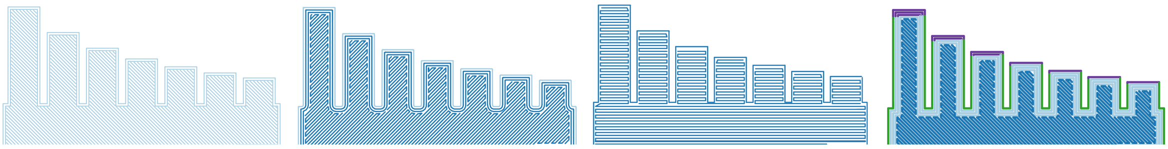
We have used the same G-Code to print both the fan cooled model and the model without fan cooling. The exact print settings and observations are listed in table 6.3.

Slicing tool	Nozzle	Layer Thickness	Cooling	Observations
Cura	$0.5mm$	$0.4mm$	no	from 15°-30° small deviations (D: $0.2 - 1mm$)
			yes	15° has small deviations (D: $0.2 - 1mm$)
KISSlicer	$0.5mm$	$0.4mm$	no	from 15°-25° large deviations (D: $1 - 2mm$)
			yes	from 15°-25° small deviations (D: $0.2 - 1mm$)
Skeinforge	$0.5mm$	$0.4mm$	no	from 15°-30° large deviations (D: $1 - 2mm$)
			yes	from 15°-30° large deviations (D: $1 - 2mm$)
Slic3r	$0.5mm$	$0.4mm$	no	from 15°-35° small deviations (D: $0.2 - 1mm$)
			yes	from 15°-20° small deviations (D: $0.2 - 1mm$)

Table 6.3: Observed results for Overhang Test

(1) Cura without fan **(2)** KISSlicer without fan **(3)** Skeinforge without fan **(4)** Slic3r without fan

(5) Cura with fan **(6)** KISSlicer with fan **(7)** Skeinforge with fan **(8)** Slic3r with fan



(9) Cura G-Code **(10)** KISSlicer G-Code **(11)** Skeinforge G-Code **(12)** Slic3r G-Code

Figure 6.3: Erroneous parts of the Overhang Test model with different slicing tools- with fan cooling and without fan cooling

In general the version without the use of a cooling fan (figures 6.3-1 - 6.3-4) are of lower quality than the same versions that were cooled during printing (figures 6.3-5-6.3-8). Nevertheless the overhangs with 45° and 40° could be printed with good quality regardless of fan cooling. Overhangs with 35° and 30° could be printed with good quality only by using fan cooling; the slicing algorithms do not seem to have a significant impact on the quality yet.

This changes for smaller angles where the quality is not good even with fan cooling. Differences between the slicing tools originate from the different extrusion speeds used. Cura (figure 6.3-9) uses the slowest extrusion speed with ~15 $\frac{mm}{s}$ and has the best result. KISSlicer, Skeinforge and Slic3r mainly extrude with ~20 $\frac{mm}{s}$ but Slic3r speeds up to ~30 $\frac{mm}{s}$ extrusion speed when printing the overhang. While Cura, KISSlicer and Slic3r remain at a constant extrusion speed throughout all layers Skeinforge constantly speeds up on the way to the top starting with ~10 $\frac{mm}{s}$ and reaching ~25 $\frac{mm}{s}$ in the top layers. In addition to that the corners of the overhangs become increasingly rounded the higher the extrusion speed becomes.

6.3 Text Test

The Text Test model [9] is a plate with 10 lines of letters with different font sizes, with the letters in each line being A, B, C, F, X, W, Q, R, a, b, g, h, i, j, x and z. The font size of the smallest line is 1 mm, the font size of the largest line is 6 mm. The first line has a height of 1 mm in the 3D model and all other lines have a height of 0.5 mm.

With this setup the model has a lot of very small details of different forms and sizes. This makes it difficult for the slicers and printers to accurately print the model. With the different font sizes we can easily identify the level of detail at which printed results have a good quality and at which level the printed quality starts to drop.

The letters expose various difficulties. One major difficulty are the round shapes of the letters B, C, Q, R, a, b, g, h and j, especially as they get smaller.
Another difficulty are intersections found in the letters A, B, F, X, Q, R, a, b, h and x. An intersection is a spot in the model where multiple extrusion lines meet (e.g. the middle of the letter X). It is not possible to extrude intersections in one line so the printer has to retract and restart again at some point. If the retraction is executed too early the printed result might have a hole. In opposition to that, if the retraction is executed too late the printed result might be a little bit higher at the intersection point. Both options lead to visible quality impacts.
As the details get smaller it is also important that the printed result is not a single smearing. With the fine level of details the nozzle often has to change between extruding and moving without extruding. As the time frames between those two states become increasingly smaller with a finer level of detail it becomes more difficult for the printer not to smear.

6.3.1 Comparing Text Test with different slicers

We used all available slicing tools to print the Text Test model. The exact settings are listed in table 6.4.

As seen in figure 6.4 the text lines 5-10 cannot be printed in good quality. Cura detects that and does not even try to print the lines, whereas the other slicing tools try and fail. It is interesting to notice that Skeinforge smears a lot between the letters and lines. Cura and KISSlicer have the clearest printed font. The result of Slic3r looks more like a serif font rather than a sans serif font as the font in the model is.

The differences can easily be explained by looking at the G-Codes of single letters in figure 6.5. The G-Codes of Cura and KISSlicer mainly contain the outline of the letters and at some points a little bit of infill. Skeinforge uses a similar approach, but puts more infill into the letters by extruding the infill in a zig-zag-pattern. Slic3r uses a very different approach at intersections compared to the other slicing tools. The intersections are printed by using a X-like extrusion pattern.

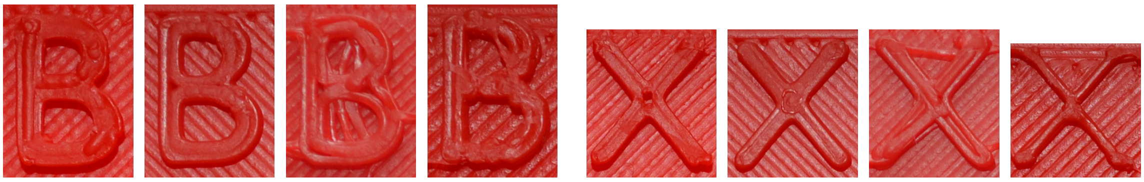
Slicing tool	Nozzle	Layer Thickness	Observations
Cura	0.5mm	0.3mm	The first four lines are readable. The fifth line is unreadable and all further lines are not being printed.
KISSlicer	0.5mm	0.3mm	The first four lines are readable. It is possible to identify the location of the fifth to the tenth line, but the characters can not at all be identified in those lines.
Skeinforge	0.5mm	0.3mm	The characters of the first five lines can be identified. From then on only the location of the lines can be identified. Skeinforge smears a lot between the letters of all font sizes. For some reason Skeinforge did no retraction between the layers.
Slic3r	0.5mm	0.3mm	The characters of the first five lines can be identified. From the sixth to the eight line only some of the letters can be identified. In the ninth and tenth line no letter can be identified.

Table 6.4: Observed results for Text Test

(1) Cura **(2)** KISSlicer

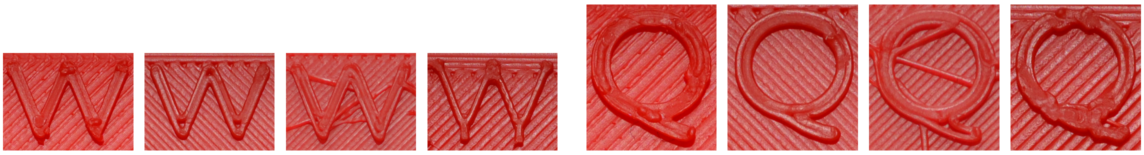
(3) Skeinforge **(4)** Slic3r

Figure 6.4: All results of the Text Test model

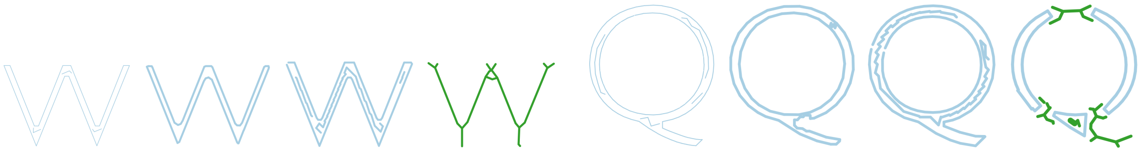


(1) Cura (2) KISS (3) Skein (4) Slic3r (5) Cura (6) KISS (7) Skein (8) Slic3r

(9) Cura (10) KISS (11) Skein (12) Slic3r (13) Cura (14) KISS (15) Skein (16) Slic3r

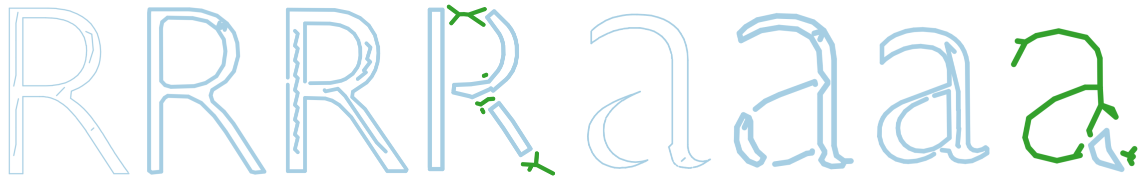


(17) Cura (18) KISS (19) Skein (20) Slic3r (21) Cura (22) KISS (23) Skein (24) Slic3r



(25) Cura (26) KISS (27) Skein (28) Slic3r (29) Cura (30) KISS (31) Skein (32) Slic3r

(33) Cura (34) KISS (35) Skein (36) Slic3r (37) Cura (38) KISS (39) Skein (40) Slic3r



(41) Cura (42) KISS (43) Skein (44) Slic3r (45) Cura (46) KISS (47) Skein (48) Slic3r

Figure 6.5: Selected letters of the Text Test with corresponding G-Codes. Used abbreviations: Cura: Cura, KISS: KISSlicer, Skein: Skeinforge, Slic3r: Slic3r

6.4 Cup Model

The Cup Model model [7] is a bulgy cup with a handle. We chose this model for this study as the cup has very slopy overhangs. Especially the beginning of the handle is a very shallow overhang that is difficult to print.

6.4.1 Comparison of slicing tools using Cup Model

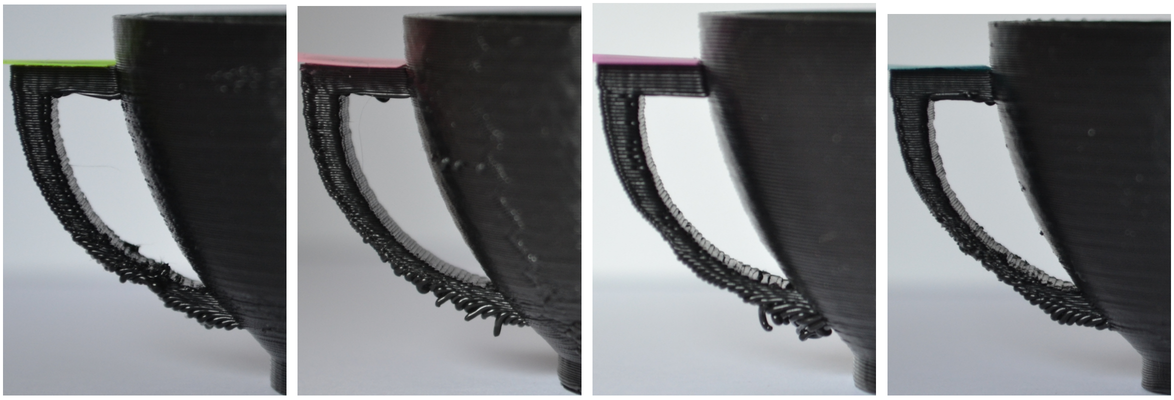
We have sliced the Cup Model model with all slicing tools using the settings listed in table 6.5. The cups have been printed with black ABS, because the black filament reflects light better than the red one which makes it easier to spot the little dents on the surface of the cups.

Slicing tool	Nozzle	Layer Thickness	Observations
Cura	$0.5mm$	$0.2mm$	The handle has minor overhangs (D: $0.2 - 1mm$).
KISSlicer	$0.5mm$	$0.2mm$	The handle has some protruding strings (D: $< 0.2mm$). A lot of tiny dents (D: $0.2 - 1mm$)are sprinkled all over the surface.
Skeinforge	$0.5mm$	$0.2mm$	The handle has some overhangs right at the beginning (D: $0.2 - 1mm$). The cup has a vertical dent at the side (D: $0.2 - 1mm$).
Slic3r	$0.5mm$	$0.2mm$	The handle has some minor overhangs (D: $< 0.2mm$).

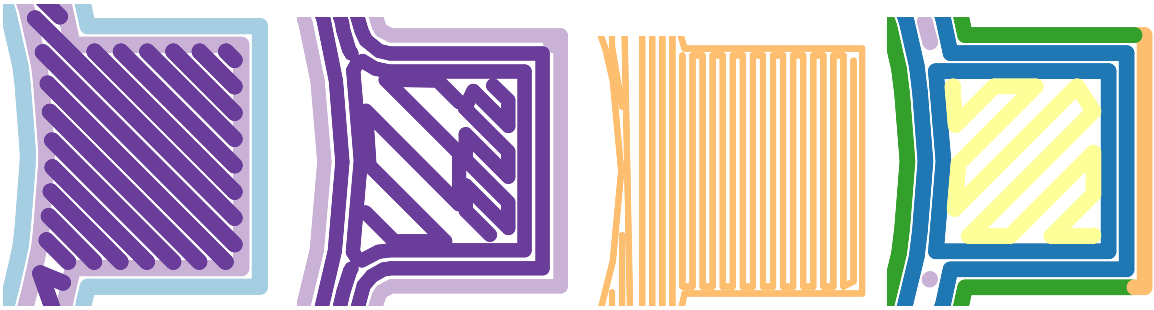
Table 6.5: Observed results for Cup Model with different slicing tools

The printed results are shown in figure 6.6. The G-Code visible in figures 6.6-5-6.6-8 is taken from the bottom beginning of the handle. As seen in figure 6.6-5), Cura extrudes a very dense pattern inside the handle which leads to the misshaped handle as the extruded filament expands in all directions. The overhangs of KISSlicer are most likely due to the fact that KISSlicer extrudes the filament with a greater density at the outer side of the handle as seen in figure 6.6-6. Skeinforge (figure 6.6-7) prints only one outer track of filament which leads to a very unstable overhang. As seen in figure 6.6-3 this leads to protruding strings. Slic3r produces a G-Code (figure 6.6-8) with extrusion speeds ranging from $10\frac{mm}{s}$ to $50\frac{mm}{s}$ and 3 outer tracks. This seems to be a good setting to keep the handle in place.

In addition to that it is very interesting to compare the different fill patterns used to fill the wall of the cup, as seen in figure 6.7. Cura uses a diagonal pattern to fill the wall. This leads to a lot of very tiny indentions and dents in the surface of the cup. The indents and dents can be seen but are hardly haptical perceivable. The surface KISSlicer generates with its dense fill pattern is a bit more rough compared to the others but still regular. There is only one big dent at the bottom where the overhang is relatively large. Skeinforge (figure 6.7-3) has a



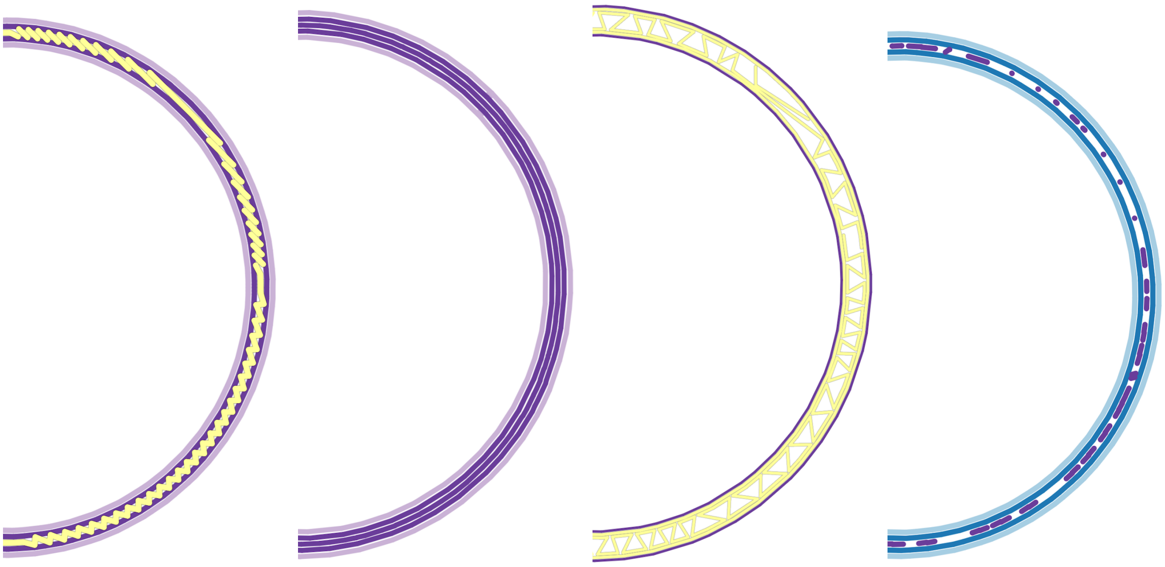
(1) Cura (2) KISSlicer (3) Skeinforge (4) Slic3r



(5) Cura (6) KISSlicer (7) Skeinforge (8) Slic3r

Figure 6.6: The handles of the Cup Model model

very irregular fill pattern at first sight, but the printed surface is very smooth and regular. The irregular fill pattern even has a fluctuating density. This fill pattern only works across multiple patterns. Skeinforge shifts the fill pattern with each layer so that high density parts are extruded where low density parts were in the layer below. With this technique the dense parts always have the possibility to trickle down before expanding sideways. Slic3r uses a technique very similar to Skeinforge as seen in figure 6.7-3 but the fill pattern is not as regular as Skeinforge's fill pattern. The dot size does not seem to follow a specific pattern but it is definitely larger if there is a lower density in the layer below. Hence the average density between the layers varies which leads to some tiny indents visible in the printed surface.



(1) Cura **(2)** KISSlicer **(3)** Skeinforge **(4)** Slic3r

Figure 6.7: The fill patterns used by the different slicing tools for the Cup Model model

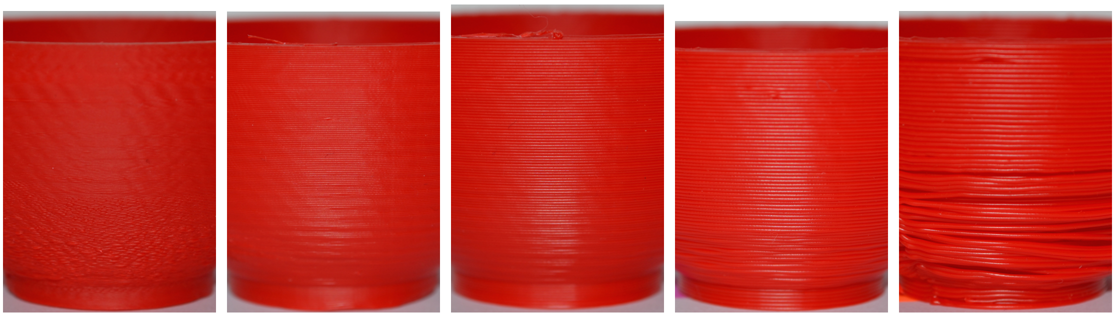
6.4.2 Comparison of layer thickness using Cup Model

We have sliced the Cup Model model with KISSlicer setting different layer thicknesses using the settings listed in table 6.6.

Slicing tool	Nozzle	Layer Thickness	Observations
KISSlicer	$0.5mm$	$0.1mm$	The surface of the cup has a slight corrugation. The bottom half of the cup has more errors than the top half of the cup (D: $0.2-1mm$). The handle has a few irregularities and bumps (D: $1-2mm$).
KISSlicer	$0.5mm$	$0.2mm$	The surface of the cup has the smoothest surface compared to the other cups and has only a few dents (D: $< 0.2mm$). The beginning of the handle has a lot of overhanging strings (D: $0.2-1mm$)while at the beginning of the handle they are removable (R).
KISSlicer	$0.5mm$	$0.3mm$	The cup has a few errors in the bottom half of the handle (D: $< 0.2mm$). The handle itself has some outstanding material (D: $0.2-1mm$)and some removable strings at the beginning of the handle (R).
KISSlicer	$0.5mm$	$0.4mm$	The surface is a lot rougher and has large dents in the bottom third of the cup (D: $0.2-1mm$). The handle has a lot of overhanging material at the beginning (D: $\geq 2mm$).
KISSlicer	$0.5mm$	$0.5mm$	The cup has a lot of free movable filament strings and is completely out of shape (C).

Table 6.6: Observed results for Cup Model with different layer thicknesses

Figure 6.8 shows the cups printed with different layer thicknesses from a frontal perspective. It is easy to see that a layer thickness of $0.2mm$ and $0.3mm$ leads to the best print result. If the layer thickness is too small, tiny errors appear in difficult sections of the model (e.g. overhangs), whereas a bigger layer thickness leads to catastrophic failures in the printed model, as seen in figure 6.8-5.



(1) 0.1mm layer thickness **(2)** 0.2mm layer thickness **(3)** 0.3mm layer thickness **(4)** 0.4mm layer thickness **(5)** 0.5mm layer thickness

Figure 6.8: Different layer thicknesses using KISSlicer as slicing tool and Cup Model model

6.5 Fine Pillars Test

The Fine Pillars Test model [4] is a tower with a square base area. The tower itself is hollow and the walls consist of multiple rectangular pillars. In total the model consists of six storeys in which the pillars width gets smaller the higher the storey is. The pillars in the first storey have a width of $4.0mm$ and the pillars in the sixth storey have a width of $0.75mm$. As the pillars become smaller, the amount of pillars per storey increases. To ensure the pillars have a steady ground a floor with a height of $1.5mm$ finishes the $5.0mm$ tall pillars in each storey.

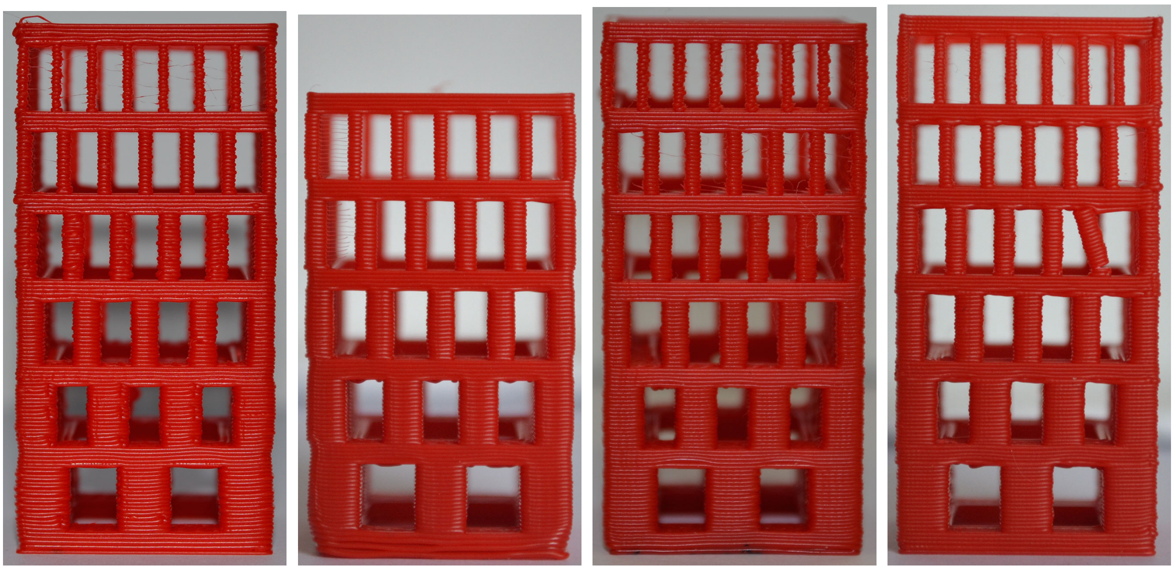
We have chosen this model to examine how the different slicing tools deal with the small and filigree pillars. The upper storeys of the model become increasingly difficult to print due to the very small pillars where each layer has to be printed on top of the previous small piece of filament.

We have printed the Fine Pillars Test model using different slicing tools using the settings listed in table 6.7.

Slicing tool	Nozzle	Layer Thickness	Observations
Cura	$0.5mm$	$0.3mm$	The printed model has some large dents in the lower storeys facing inwards (D: $0.2 - 1mm$). The pillars have a very tiny sidewards deviation (D: $< 0.2mm$).
KISSlicer	$0.5mm$	$0.3mm$	The sixth storey was not printed (M: $\geq 8mm$). In fact the top pillars were not printed, but KISSlicer tried to print the floor on top of that and extruded the material in midair, which then fell onto the model. The pillars have a very even width and no sidewards deviation at all.
Skeinforge	$0.5mm$	$0.3mm$	The pillars have a very even width. The floors in between the layers are slightly bent up- and downwards (D: $< 0.2mm$). In addition to that there is one larger piece of material on the outside wall (D: $0.2 - 1mm$). The thinest pillars are very fragile because Skeinforge tries to print rectangles instead of crosses like Cura and Slic3r.
Slic3r	$0.5mm$	$0.3mm$	The pillars have a very even width, but during the print three pillars were accidentally knocked over by the moving nozzle (D: $1 - 2mm$).

Table 6.7: Slicing tool settings and observed results for Fine Pillars Test with different slicing tools

As seen in figure 6.10 the slicing tools use different fill patterns to print the pillars. Some fill patterns correlate with the quality impacts observed in the printed objects. For example,



(1) Cura **(2)** KISSlicer **(3)** Skeinforge **(4)** Slic3r

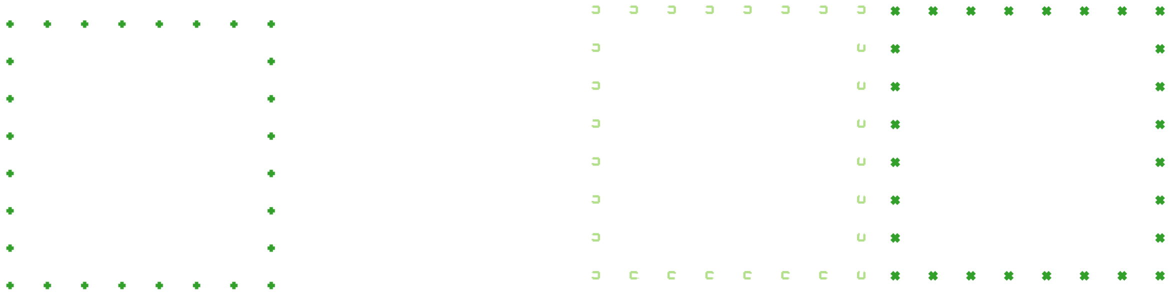
Figure 6.9: The Fine Pillars Test model results from the different slicing tools

KISSlicer and Skeinforge extrude very much material in storey two as seen in figure 6.10-1 and figure 6.10-3 which leads to pillars with minor deviations. In opposition to that, the pillars in the same storey printed by KISSlicer (figure 6.10-2)) and Slic3r (figure 6.10-4) are of equal width, as they do not extrude too much material inside the pillar. The same behavior can also be examined in storey 4 where Cura (figure 6.10-1) has very uneven pillars due to the little bit of extra material extruded inside the pillar. The other slicing tools do not extrude extra material in that storey (figure 6.10-2-6.10-4) and thus have straight and even pillars.

(1) Cura storey 2 **(2)** KISSlicer storey 2 **(3)** Skeinforge storey 2 **(4)** Slic3r storey 2

(5) Cura storey 3 **(6)** KISSlicer storey 3 **(7)** Skeinforge storey 3 **(8)** Slic3r storey 3

(9) Cura storey 4 **(10)** KISSlicer storey 4 **(11)** Skeinforge storey 4 **(12)** Slic3r storey 4



(13) Cura storey 6 **(14)** KISSlicer storey 6 **(15)** Skeinforge storey 6 **(16)** Slic3r storey 6

Figure 6.10: G-Codes for the Fine Pillars Test model in different layers

6.6 Precision Test

Using the knowledge gathered in the previous models, we have developed a custom model to test all difficulties in parametrized varieties. The Precision Test model [6] consist of two parts. One part is used to test small and fragile geometric objects and the other part is used to test overhangs and bridges. In this section we will first present the first part of the Precision Test model and after that will continue with the second part of the model.

6.6.1 Precision Test: geometric objects

Precision Test is a plate with different objects printed on it. The objects on the plate include straight towers, triangular towers, round arcs to lancet arcs, round and square pillars with and without holes, holes in the ground plate, oval pillars, one bridge, stairs and cubes. We have listed the used slicer settings in table 6.8.

Slicing tool	Nozzle	Layer Thickness	Observations
Cura	$0.5mm$	$0.3mm$	Cura did not print two thin walls and a small hollow pillar (M: $\geq 8mm$). In addition to that the triangular pillars are too small as a part of their top was not printed (M: $1-2mm$).
KISSlicer	$0.5mm$	$0.3mm$	A bridge has overhanging strings (R). The two triangular pillars are too small as a part of their top was not printed (M: $1-2mm$).
Skeinforge	$0.5mm$	$0.3mm$	Skeinforge does not fill the ground plate next to the holes well, little additional holes are visible (M: $< 1mm$). The two triangular pillars are too small as a part of their top was not printed (M: $1-2mm$). The cube has a long trench on the top (M: $1-2mm$).
Slic3r	$0.5mm$	$0.3mm$	Slic3r knocked over one of the pillars (D: $1-2mm$). Small dents are visible at the top point of the round arcs (D: $0.2-1mm$).

Table 6.8: Slicing tool settings and observed results for Precision Test with different slicing tools

In order to analyze this model we used a digital caliper to measure a selected set of objects. The chosen locations are shown in figure 6.11 and the respective results are listed in figure 6.12.

All slicing tools print the measured pillars 04 and 05 up to $1mm$ too thick, whereas the hollow pillar 06 is perfectly sized. When looking at the G-Code of the three pillars there is one basic difference: the filled pillars have multiple outer walls extruded, whereas the

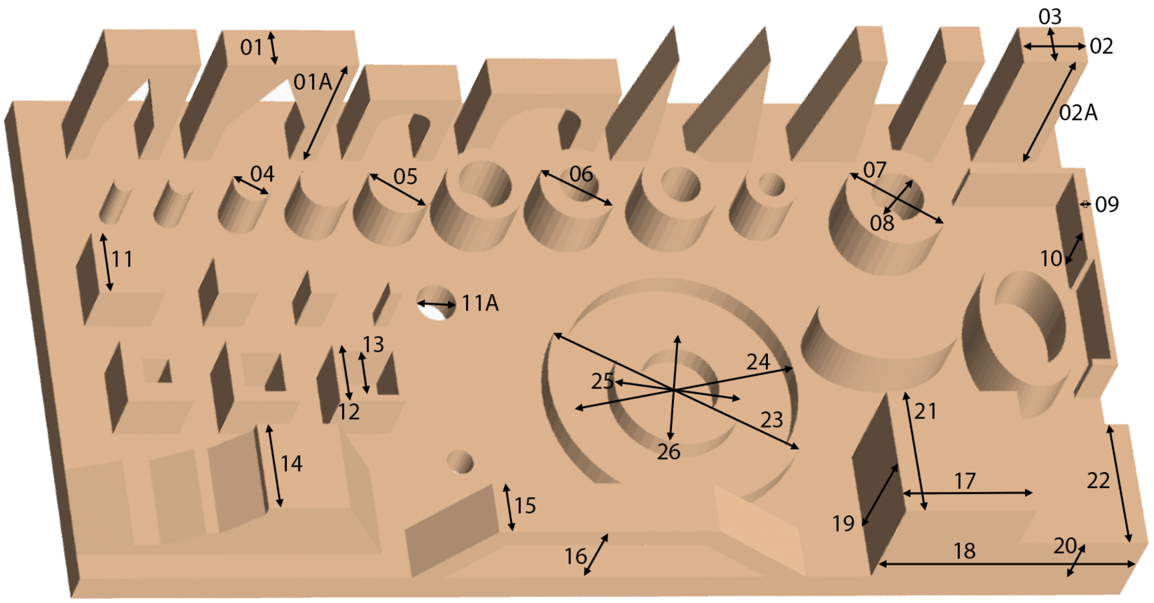


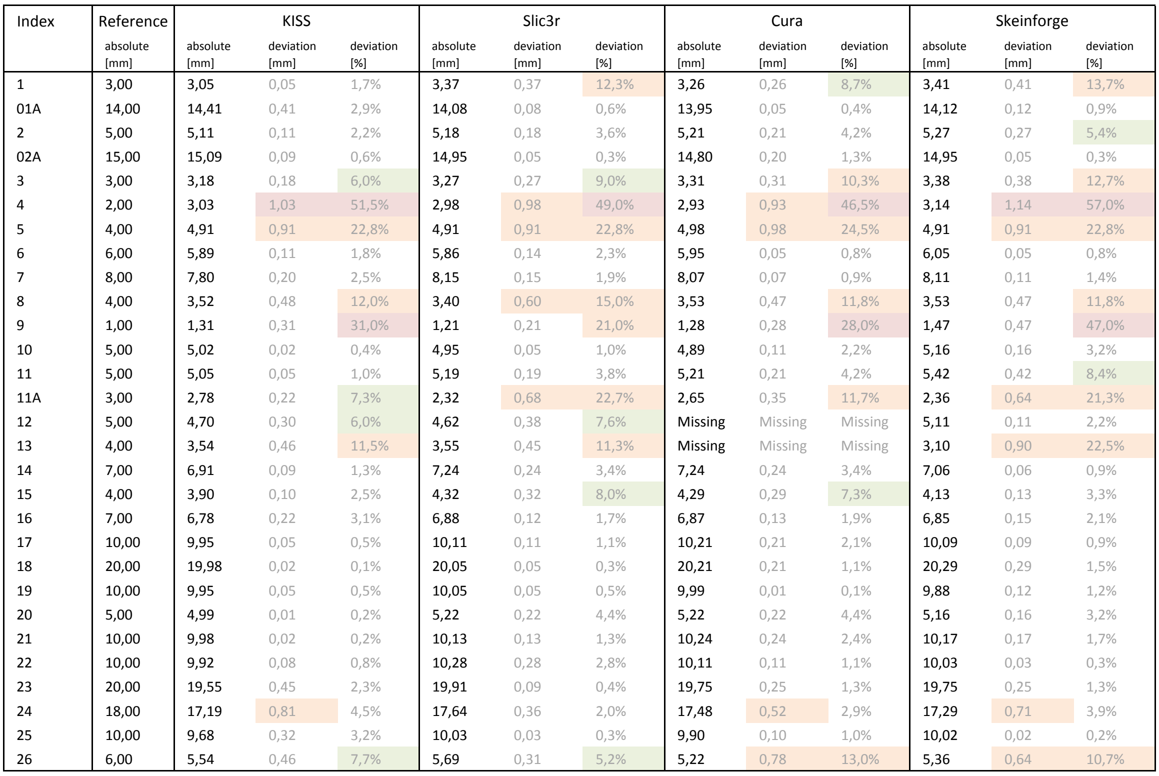
Figure 6.11: Locations measured with the caliper in Precision Test

hollow pillar has two simple walls - one for the inside and one for the outside. The infill is then done by randomly extruding small bits of filament. Hence less material pushes against the outside wall and the pillar keeps in place.

Measurement 07 is the width of the outer wall of a hollow pillar and measurement 08 is the width of the hole. Interestingly, the width of the inner circle has a much larger deviation than the outer circle. Nevertheless it is difficult to identify the reason for this behavior. The different G-Codes (see figure 6.14) use a similar amount of infill and some even use the same fill patterns, so it is not possible to identify a certain G-Code pattern with the deviation. In addition to that a temporal analysis is also inconclusive. Cura and Slic3r extrude the inner wall first and the outer wall last, whereas KISSlicer and Skeinforge extrude the outer wall first and the inner wall last.

Measurement 12 (outer width) and 13 (inner width) of a hollow cube show a similar behavior. The cube has in fact a very small wall width of $1mm$ and Cura decided to not slice the cube at all. Skeinforge has a deviation of the inner width that is two times as large as the deviation of KISSlicer and Slic3r. This is due to the fact that Skeinforge extrudes two rounds of filament for the wall whereas the other two slicing tools extrude only one round.

In figure 6.13 there are the G-Codes of different layers of the holes that are in the ground plate of the Precision Test model. It is interesting to see the different techniques the slicing tools use when approaching holes as seen in figures 6.13-1-6.13-4. The slicing tools also apply different slicing techniques while extruding the infill around the holes as seen in figures 6.13-5-6.13-8. However, the approaches seen in figures 6.13-9-6.13-12 are the approaches that are used to extrude the surfacing layer around the hole and thus the visible ones. The printed



Index	Reference	KISS			Slic3r			Cura			Skeinforge		
	absolute [mm]	absolute [mm]	deviation [mm]	deviation [%]	absolute [mm]	deviation [mm]	deviation [%]	absolute [mm]	deviation [mm]	deviation [%]	absolute [mm]	deviation [mm]	deviation [%]
1	3,00	3,05	0,05	1,7%	3,37	0,37	12,3%	3,26	0,26	8,7%	3,41	0,41	13,7%
01A	14,00	14,41	0,41	2,9%	14,08	0,08	0,6%	13,95	0,05	0,4%	14,12	0,12	0,9%
2	5,00	5,11	0,11	2,2%	5,18	0,18	3,6%	5,21	0,21	4,2%	5,27	0,27	5,4%
02A	15,00	15,09	0,09	0,6%	14,95	0,05	0,3%	14,80	0,20	1,3%	14,95	0,05	0,3%
3	3,00	3,18	0,18	6,0%	3,27	0,27	9,0%	3,31	0,31	10,3%	3,38	0,38	12,7%
4	2,00	3,03	1,03	51,5%	2,98	0,98	49,0%	2,93	0,93	46,5%	3,14	1,14	57,0%
5	4,00	4,91	0,91	22,8%	4,91	0,91	22,8%	4,98	0,98	24,5%	4,91	0,91	22,8%
6	6,00	5,89	0,11	1,8%	5,86	0,14	2,3%	5,95	0,05	0,8%	6,05	0,05	0,8%
7	8,00	7,80	0,20	2,5%	8,15	0,15	1,9%	8,07	0,07	0,9%	8,11	0,11	1,4%
8	4,00	3,52	0,48	12,0%	3,40	0,60	15,0%	3,53	0,47	11,8%	3,53	0,47	11,8%
9	1,00	1,31	0,31	31,0%	1,21	0,21	21,0%	1,28	0,28	28,0%	1,47	0,47	47,0%
10	5,00	5,02	0,02	0,4%	4,95	0,05	1,0%	4,89	0,11	2,2%	5,16	0,16	3,2%
11	5,00	5,05	0,05	1,0%	5,19	0,19	3,8%	5,21	0,21	4,2%	5,42	0,42	8,4%
11A	3,00	2,78	0,22	7,3%	2,32	0,68	22,7%	2,65	0,35	11,7%	2,36	0,64	21,3%
12	5,00	4,70	0,30	6,0%	4,62	0,38	7,6%	Missing	Missing	Missing	5,11	0,11	2,2%
13	4,00	3,54	0,46	11,5%	3,55	0,45	11,3%	Missing	Missing	Missing	3,10	0,90	22,5%
14	7,00	6,91	0,09	1,3%	7,24	0,24	3,4%	7,24	0,24	3,4%	7,06	0,06	0,9%
15	4,00	3,90	0,10	2,5%	4,32	0,32	8,0%	4,29	0,29	7,3%	4,13	0,13	3,3%
16	7,00	6,78	0,22	3,1%	6,88	0,12	1,7%	6,87	0,13	1,9%	6,85	0,15	2,1%
17	10,00	9,95	0,05	0,5%	10,11	0,11	1,1%	10,21	0,21	2,1%	10,09	0,09	0,9%
18	20,00	19,98	0,02	0,1%	20,05	0,05	0,3%	20,21	0,21	1,1%	20,29	0,29	1,5%
19	10,00	9,95	0,05	0,5%	10,05	0,05	0,5%	9,99	0,01	0,1%	9,88	0,12	1,2%
20	5,00	4,99	0,01	0,2%	5,22	0,22	4,4%	5,22	0,22	4,4%	5,16	0,16	3,2%
21	10,00	9,98	0,02	0,2%	10,13	0,13	1,3%	10,24	0,24	2,4%	10,17	0,17	1,7%
22	10,00	9,92	0,08	0,8%	10,28	0,28	2,8%	10,11	0,11	1,1%	10,03	0,03	0,3%
23	20,00	19,55	0,45	2,3%	19,91	0,09	0,4%	19,75	0,25	1,3%	19,75	0,25	1,3%
24	18,00	17,19	0,81	4,5%	17,64	0,36	2,0%	17,48	0,52	2,9%	17,29	0,71	3,9%
25	10,00	9,68	0,32	3,2%	10,03	0,03	0,3%	9,90	0,10	1,0%	10,02	0,02	0,2%
26	6,00	5,54	0,46	7,7%	5,69	0,31	5,2%	5,22	0,78	13,0%	5,36	0,64	10,7%

Figure 6.12: Results of the measurement of Precision Test with the caliper

holes are shown in figure 6.16. Cura's technique is very good as the area around the holes are nearly not distinguishable from the rest of the ground plate. KISSlicer uses a very similar technique but the area right before the holes in the direction of the extrusion movement are very good visible and have a slightly rough surface. Skeinforge extrudes a little bit too little material around the holes so that tiny holes of missing filament are perceivable right next to the border of the actual hole. slicing tool uses a very large border around the holes which interrupts the regular pattern of the ground plate and leads to a greater area with a rougher surface.

The wall with different widths on the right side of the model (see figure 6.16) is interesting to examine at the G-Code level. The reason for the wall not being fully printed by Cura is that the G-Code does not contain the whole wall. The small offset at the end of the wall is also not sliced by KISSlicer. Nevertheless the height of the wall (compare figure 6.12, measurement 10) is very accurate amongst all slicing tools. However the width of the wall varies up to 50% (compare figure 6.12, measurement 09) with Skeinforge having the worst deviation of $0.47mm$ and Slic3r having the best deviation of $0.21mm$. The huge deviation of Skeinforge can be explained by looking at the G-Code in figure 6.14-3 as Skeinforge extrudes an infill into the wall whereas the others do not.

Comparing the G-Codes of the hollow ovals in 6.14 there is a slight difference be-

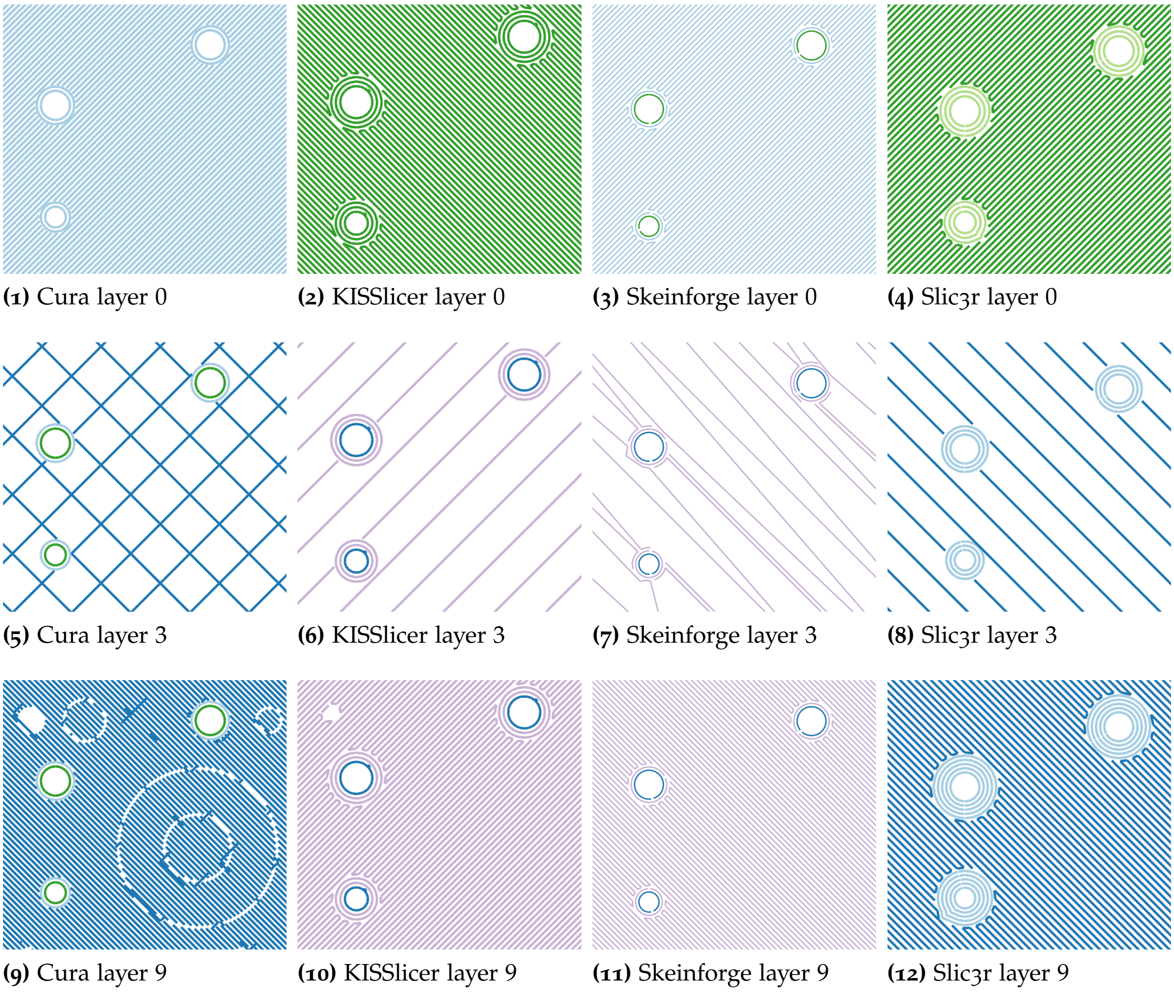
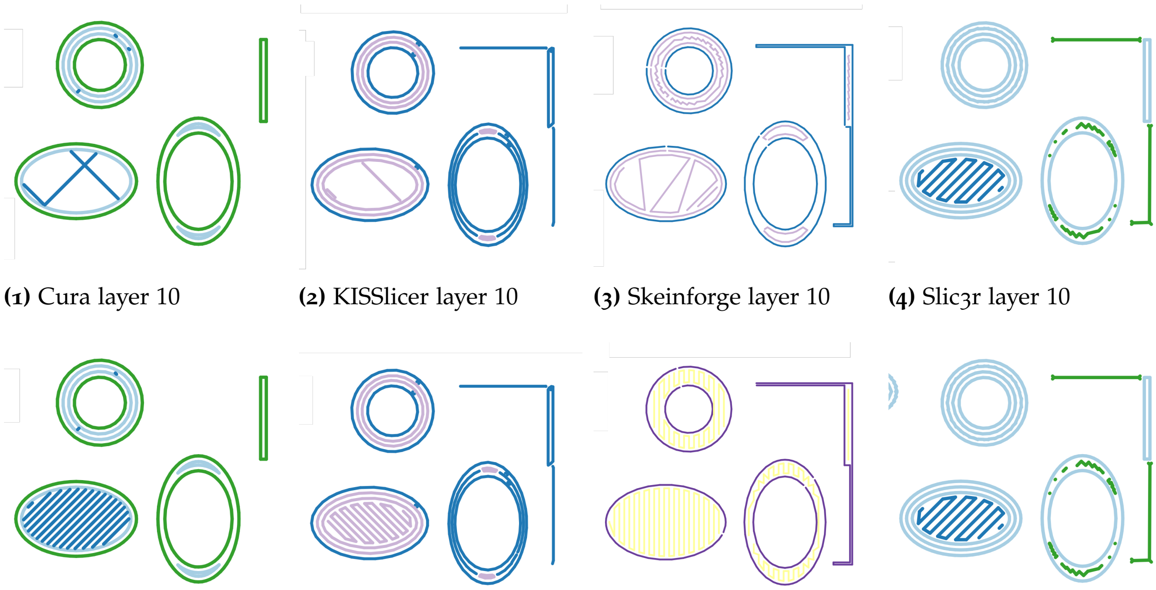

(1) Cura layer 0
(2) KISSlicer layer 0
(3) Skeinforge layer 0
(4) Slic3r layer 0
(5) Cura layer 3
(6) KISSlicer layer 3
(7) Skeinforge layer 3
(8) Slic3r layer 3
(9) Cura layer 9
(10) KISSlicer layer 9
(11) Skeinforge layer 9
(12) Slic3r layer 9

Figure 6.13: G-Code snippets of the holes in the ground plate for the Precision Test model in different layers

tween the infill patterns used by the different slicing tools. The differences do not have an impact on the actual wall of the oval but looking at the oval from the top the infill pattern of Cura and Slic3r (figures 6.16-1 and 6.16-4) leads to little visible holes in the surface whereas the more dense infill pattern applied by KISSlicer and Skeinforge does not produce holes (compare to 6.16-2 and 6.16-3).
Despite the different fill patterns used for the solid oval and the different techniques used for the surface of the solid oval by all the slicing tools as seen in figure 6.14 it is not possible to identify quality impacts either in shape precision, surface roughness or the actual size.

In this section we will examine the impact of the different slicing techniques on the pillars and arcs. The printed results are shown in figures 6.16-5-6.16-8 with the corresponding G-Codes in figure 6.15. In general, the towers and pillars produced by Slic3r have a slightly smoother surface than the other slicing tools. This is mainly due to the fact that Slic3r


(1) Cura layer 10 **(2)** KISSlicer layer 10 **(3)** Skeinforge layer 10 **(4)** Slic3r layer 10

(5) Cura layer 26 **(6)** KISSlicer layer 26 **(7)** Skeinforge layer 26 **(8)** Slic3r layer 26

Figure 6.14: G-Code snippets of the oval pillars for the Precision Test model in different layers

generally slices all G-Code rows a bit further apart than the other slicing tools. Nevertheless, the overall quality of the pillars and towers is equivalent even though the slicing tools use different infill techniques. In figure 6.15 we show layer 10, 36 and 37 of each slicing tool. Layer 10 is the layer right above the ground plate and contains the beginning of all pillars, towers and arcs which have different infill patterns depending on the width and length of the shape. Layer 36 and 37 give a brief overview of the slicing techniques used for the arcs. It can be seen how the pillars of the fourth arc are being connected by the different slicing tools. Even though KISSlicer and Slic3r use a similar pattern to connect the pillars Slic3r has bit of protruding filament on the inner side of the round arcs. This is most likely due to the different extrusion speeds used, as KISSlicer extrudes at $35\frac{mm}{s}$ and Slic3r extrudes at $25\frac{mm}{s}$. A major difficulty for the slicing tools are the triangular towers which resulted in very different heights as seen in figures 6.16-5-6.16-8. This can be explained by the threshold levels the different slicing tools apply to filigree structures. The top of the triangular towers has not been sliced by Cura, KISSlicer and Skeinforge, in fact only Slic3r sliced the top of the triangular towers and the printed result still has a very good quality (see figure 6.16-8).

(1) Cura layer 10

(2) KISSlicer layer 10

(3) Cura layer 36

(4) KISSlicer layer 36

(5) Cura layer 37

(6) KISSlicer layer 37

(7) Skeinforge layer 10

(8) Slic3r layer 10

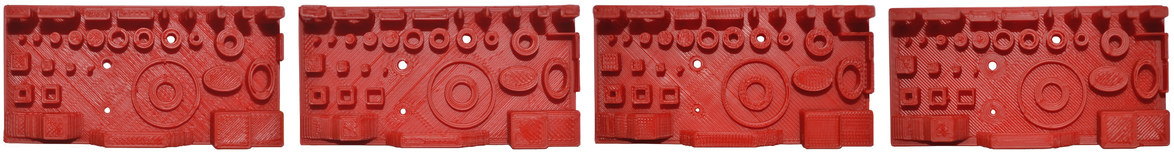
(9) Skeinforge layer 36

(10) Slic3r layer 36

(11) Skeinforge layer 37

(12) Slic3r layer 37

Figure 6.15: G-Code snippets of the pillars for the Precision Test model in different layers

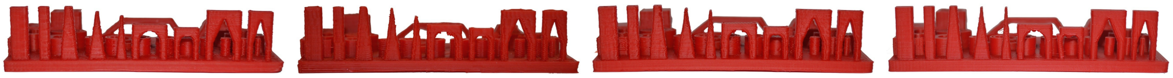


(1) Cura

(2) KISSlicer

(3) Skeinforge

(4) Slic3r



(5) Cura

(6) KISSlicer

(7) Skeinforge

(8) Slic3r

Figure 6.16: The Precision Test model photographed from the top and from the side

6.7 Adhesion and Bridging Test

Adhesion and Bridging Test [3] is a model containing a large tower with a triangular denting at the top, a solid staircase, straight and sloped bridges and holes of different shapes and sizes in the ground plate. We used this model to examine the different techniques used to print bridges and to measure the adhesion of the model on the print bed.

6.7.1 Comparison of bridging techniques

Bridging is one of the more challenging tasks for a FDM printer when no support structures are used. In figure 6.17 a horizontal bridge is visible from a front view. At a first glance Cura and Skeinforge seem to create undulated bridges, KISSlicer has some large overhangs below the bridge and Slic3r has a very perfect bridge. Figure 6.18 contains the G-Codes of the first layer of all bridges. Even though Cura and Skeinforge show similar results the corresponding G-Codes do not have similarities. In fact, the Skeinforge G-Code is more similar to the G-Code of Slic3r because Skeinforge and Slic3r speed up a lot when bridging (up to $40\frac{mm}{s}$). The major difference between Skeinforge and Slic3r is in the layer atop of the first bridge layer where Skeinforge keeps the same pace and extrudes in orthogonal movements to the first layer whereas Slic3r slows down and extrudes in a usual surface pattern. The protruding filament strings produced by KISSlicer are due to the fact that KISSlicer extrudes the bridge in a rather slow diagonal movement. Cura also extrudes slow but the angle to the direction of the bridge is smaller and Cura fixes the diagonal paths to the borders of the bridge which were extruded before. KISSlicer turns around before reaching the border of the bridge and thus extrudes the bridge pattern in mid-air.

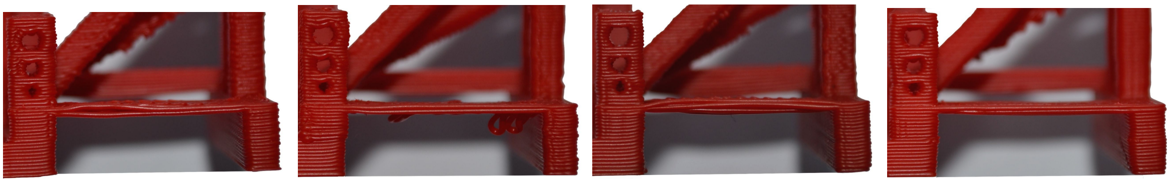

(1) Cura **(2)** KISSlicer **(3)** Skeinforge **(4)** Slic3r

Figure 6.17: Bridges

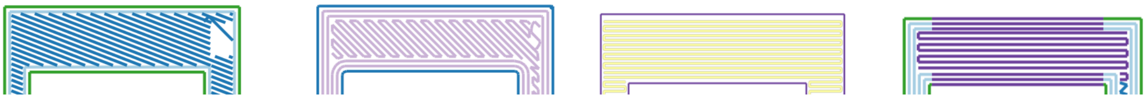

(1) Cura **(2)** KISSlicer **(3)** Skeinforge **(4)** Slic3r

Figure 6.18: Bridges

6.7.2 Comparison of the slicing techniques used around holes

The printed result of the holes in the ground plate are shown in figure 6.20. In general the holes themselves have a very good precision concerning the shape of the hole regardless of the used slicing tool. A bigger difference can only be seen at the small hole in the upper left quarter of the model. KISSlicer produced the largest whole, followed by Cura and Slic3r, whereas the hole produced by Skeinforge is rather small. The hole is smaller because the extruded filament extends into the hole and thus lessens the diameter. This also becomes clear when looking at the G-Code of Skeinforge as seen in figure 6.21-7 where Skeinforge extrudes much more filament compared to the other slicing tools between the small hole and the larger hole right above the small one.
Taking a look at figures 6.21-1-6.21-4 it is interesting to compare the different infill techniques used by the different slicing tools. All slicing tools have in common that they extrude at least two rounds of filament around all holes. This ensures the shape stability of the holes. Nevertheless the infill techniques differ and the differences is especially significant when the holes are close to each other. For example, KISSlicer (see figure 6.21-2) generally extrudes three rounds of filament around holes and thus the third round of filament around the "U"-shaped hole at the bottom of the model overlaps with the third round of the square hole right above the "U"-shaped hole which leads to a rather uneven surface as seen in figure 6.20-2. On the other hand, Skeinforge seems to extrude too little filament at that position and even more severe at the unshaped hole which leads to small visible holes in the surface around the holes. Slic3r surrounds holes on the surface layer with multiple rounds of filament which leads to a uneven surface compared to Cura. As Cura uses less rounds around the holes on the surface level there is more space remaining in order to create a more consistent fill pattern across the surface.

6.7.3 Comparison of the staircase techniques

We have printed two diagonal upward beams with different angles as seen in figure 6.22. KISSlicer has produced the best beams with nearly no overhangs, followed by Skeinforge with little overhangs, followed by Slic3r with large overhangs on the beam with the smaller angle and Cura which has a very rough surface with large overhangs. The quality differences can be explained by the corresponding G-Codes in figure 6.19. The first G-Code row shows layer 20 which is the first layer of the diagonal beams. The second G-Code row shows layer 40 which is about in the middle of the beam with the shallower angle and the third G-Code row show layer 60 which is nearly at the top of the beam with the shallower angle. The used patterns do not seem to vary between the different layers of each slicing tool. Interestingly, the extrusion speeds vary between the different layers for KISSlicer, Skeinforge and Slic3r- they all slow down when reaching higher layers. Only Cura extrudes with a rather slow but constant speed across all layers. However, the extrusion speed cannot directly be correlated with the print quality as the fill pattern seems to have a higher impact on the quality than the speed.

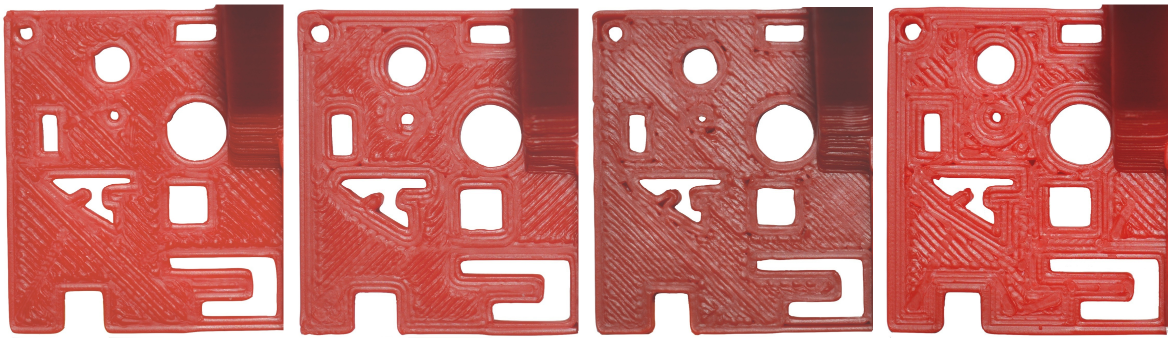
Cura extrudes a very dense infill inside the beam which expands and pushes the border of the beam to the outside leading to the highly malformed beam. Skeinforge has a very irregular infill pattern which leads to some small irregularities in the printed model as the irregularities in the pattern do not seem to perfectly cancel each other out. The most interesting observation concerning the G-Codes is that KISSlicer and Slic3r use the exact same fill pattern, but with slightly different extrusion speeds. However, the quality of KISSlicer is nearly perfect whereas the quality of Slic3r is devastating. The reason for this is that Slic3r extrudes the innermost round first and continues to extrude the next outer one whereas KISSlicer extrudes the outer round first and after that continues with the inner rounds. This difference in the extrusion order is the main cause for the different results achieved.

(1) Cura layer 20 **(2)** KISSlicer layer 20 **(3)** Skeinforge layer 20 **(4)** Slic3r layer 20

(5) Cura layer 40 **(6)** KISSlicer layer 40 **(7)** Skeinforge layer 40 **(8)** Slic3r layer 40

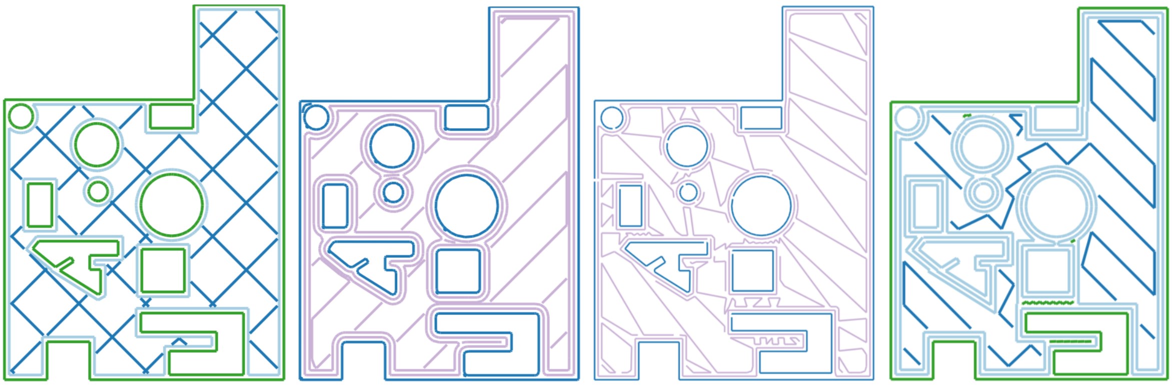
(9) Cura layer 60 **(10)** KISSlicer layer 60 **(11)** Skeinforge layer 60 **(12)** Slic3r layer 60

Figure 6.19: G-Code of stairs

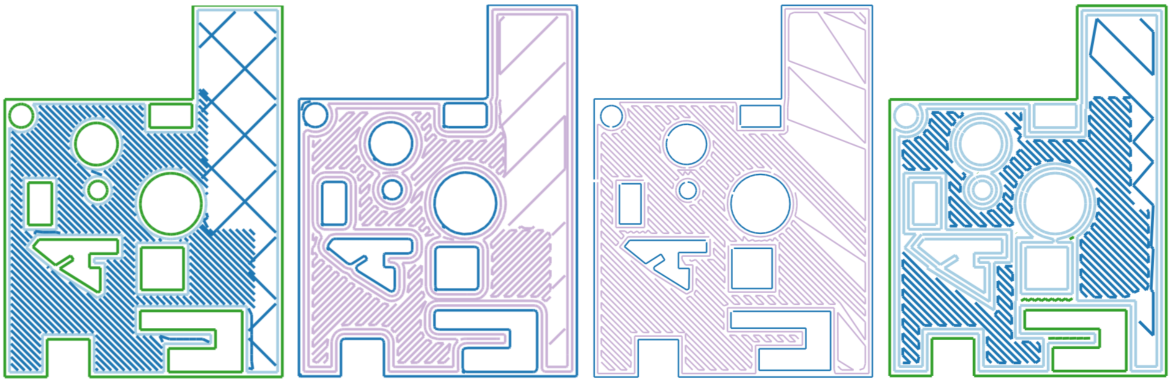


(1) Cura **(2)** KISSlicer **(3)** Skeinforge **(4)** Slic3r

Figure 6.20: Holes

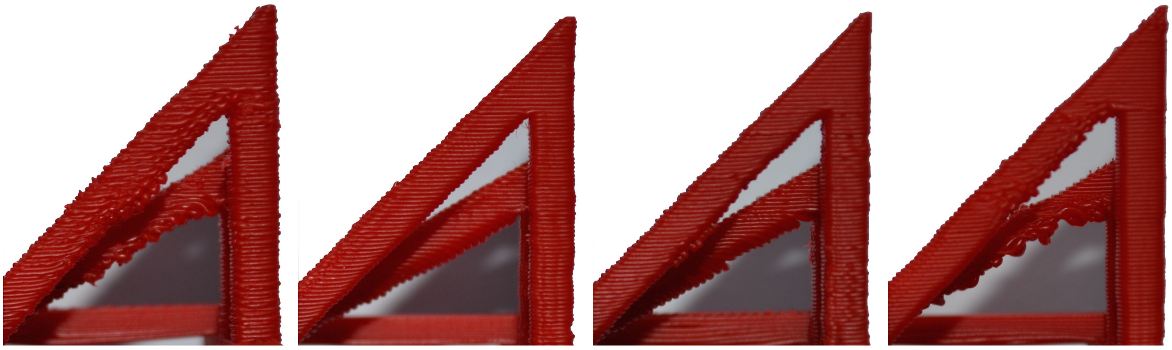


(1) Cura **(2)** KISSlicer **(3)** Skeinforge **(4)** Slic3r



(5) Cura **(6)** KISSlicer **(7)** Skeinforge **(8)** Slic3r

Figure 6.21: G-Code of holes



(1) Cura **(2)** KISSlicer **(3)** Skeinforge **(4)** Slic3r

Figure 6.22: Print result of the stair techniques

6.7.4 Comparison of the adhesion to the print bed

Good print bed adhesion is one foundation of successful FDM printing. Without good adhesion the model can warp at the bottom or even peel off the print bed.
Achieving good adhesion is more difficult for complex bottom layers than for a simple flat plate. Our model has different shapes and sizes in the ground plate to test how good the slicing tools can print a complex bottom plate.
For measuring the adhesion force we pulled the model at a fixed position directly after the last layer was printed. The measurement result was the maximum pull force before the model was pulled off. We measured the pull force with a spring scale as described in **4.2.3**. The picture **6.23** illustrates how the pull measurements were done.

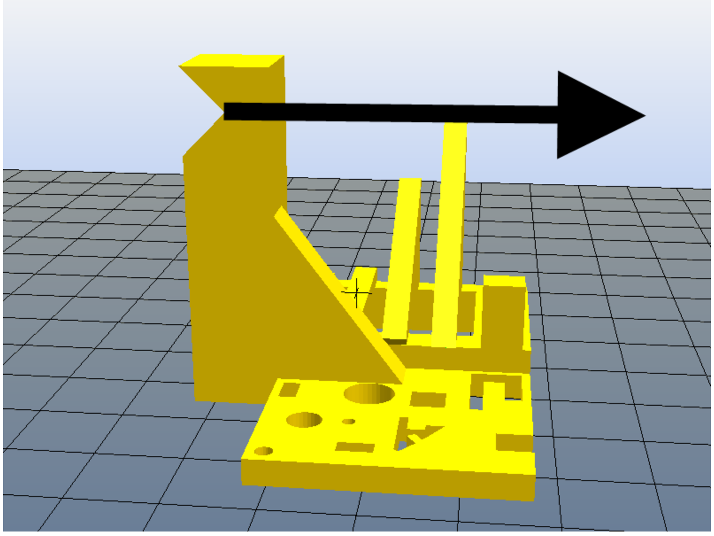
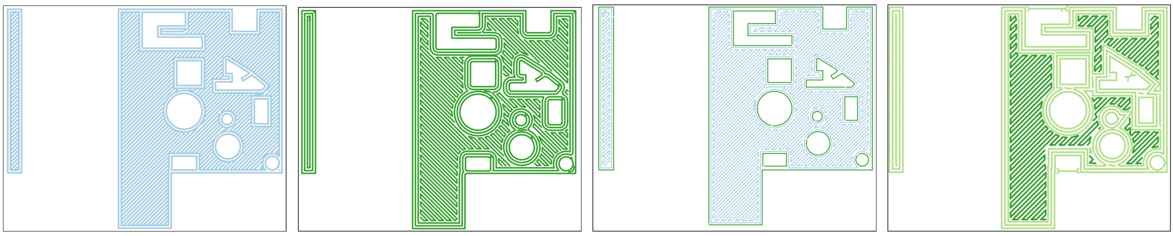


Figure 6.23: Pull test Adhesion and Bridging Test

The G-Codes of the first layers in **6.24** show the different toolpath strategies for the bottom layer.
Cura, KISSlicer and Skeinforge have similar toolpath patterns. Only Slic3r has a different strategy - it extrudes the double amount while having twice the distance between the beads. This can help with bumpy print beds when printing without raft.



(1) Cura **(2)** KISSlicer **(3)** Skeinforge **(4)** Slic3r

Figure 6.24: First layer of Adhesion and Bridging Test

Table **6.9** shows the results of the pull measurements with the spring scale in Newton. Cura, KISSlicer and Skeinforge have very similar results, as well as the have similar G-Codes. Slic3r has worse print bed adhesion. It is still good but the different fill pattern has a negative impact on the adhesion.

Slicing tool	Print bed Adhesion (N)
Cura	13
KISSlicer	15
Skeinforge	15
Slic3r	9

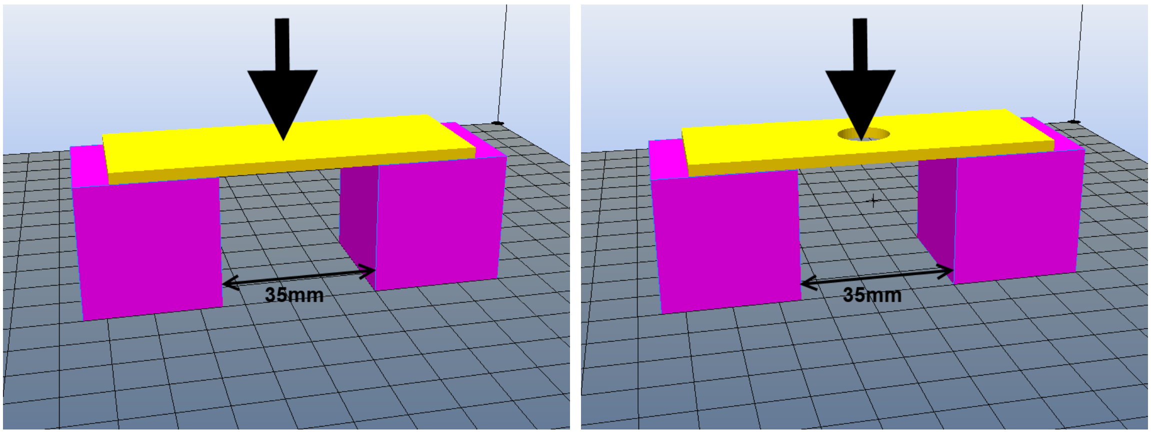
Table 6.9: Printbed adhesion (in Newton)

6.8 Strain Tests

One more quality aspect of printed parts is the strength. Therefore we did strain tests for testing the fracture and tensile strength of the printed models to analyze if there are differences between the slicing tools.

We did two fracture tests as shown in figure **6.25** - one with a solid plate and one with a plate with a hole in the middle [5]. For measuring the fracture strength we strained the plates with increasing force as shown with the arrow in the both figures. The strength of the model is represented by the last measured force before the model broke.

We also did one tensile strength test by with pulling with increasing force a model [8] of thin pillars as shown in figure **6.26**.



(1) Solid **(2)** With Hole

Figure 6.25: Test setting for plate fracture test

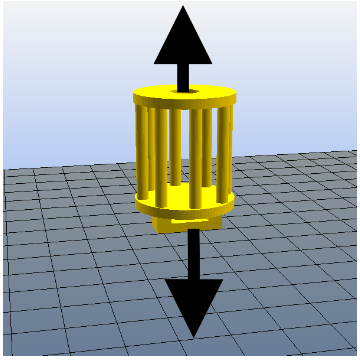


Figure 6.26: Test setting for tensile strength test

Table **6.10** shows the strength measurements (in Newton). In all fracture tests all slicing tool have very similar results.
The tensile strengths of Cura, KISSlicer and Slic3r are also very similar, only Skeinforge has a lower tensile strength. In general Skeinforge has problems with fragile structures as also shown in the test **6.5**.

	Cura	KISSlicer	Skeinforge	Slic3r
Fracture Strength	140 N	140 N	130 N	150 N
Fracture Strength, hole	80 N	90 N	90 N	90 N
Tensile Strength	290 N	320 N	190 N	310N

Table 6.10: Fracture and Tensile Strengths

Chapter 7

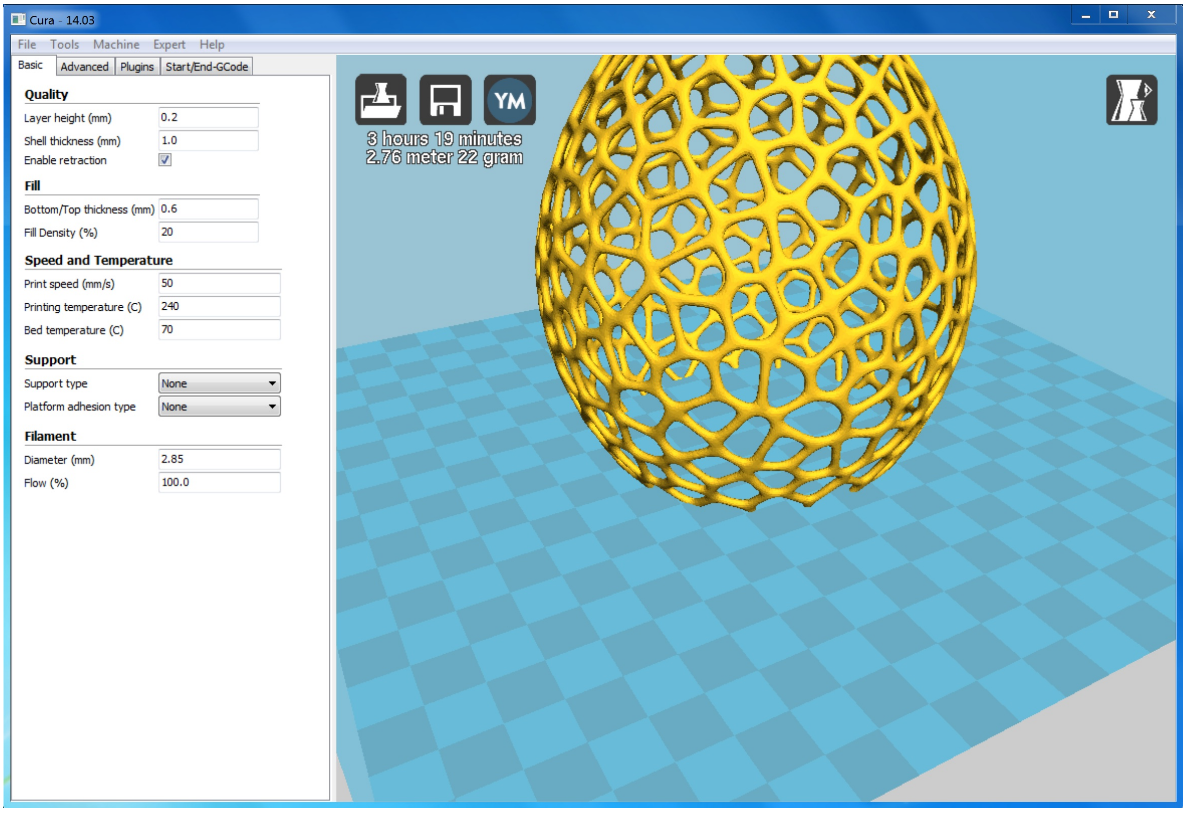
Usability of Slicing Tools

This section analyses the user experience of the slicing tools- the user interface and the performance. As described in chapter 3, a slicing tool converts a digital 3D model into printing instructions for the 3D printer and cuts the model into horizontal layers.
The different slicing tools are executable applications - executable as command-line application and/or as standalone application.

7.1 User Interface and Usability

Cura

Cura has a well-arranged 2-columns-layout (figure 7.3). On the left side are the setting possibilities which are distributed in different tabs. On the right side is the view of the model and the buttons with main functionalities like loading and saving the model. On the view you can also edit the model with the following operations: *rotate*, *scale* and *mirror*. The switching of the view mode is also possible. There are for example the view mode *Layers*, *Transparent*, *Overhang* and *Normal* (figure 7.2-1). If you select the *Layers* view mode you can see the movement lines of the extruder for each layer of the model (figure 7.2-3).
Cura offers a medium amount of settings, there are less settings compared to the other slicing tools. Its focus is on a user-friendly interface.
Cura does not provide separate profiles for different categories but profile loading and saving for all settings as well as loading settings from Cura G-Code.



Quality

Layer height (mm)	0.2
Shell thickness (mm)	1.0
Enable retraction	☑

Fill

Bottom/Top thickness (mm)	0.6
Fill Density (%)	20

Speed and Temperature

Print speed (mm/s)	50
Printing temperature (C)	240
Bed temperature (C)	70

Support

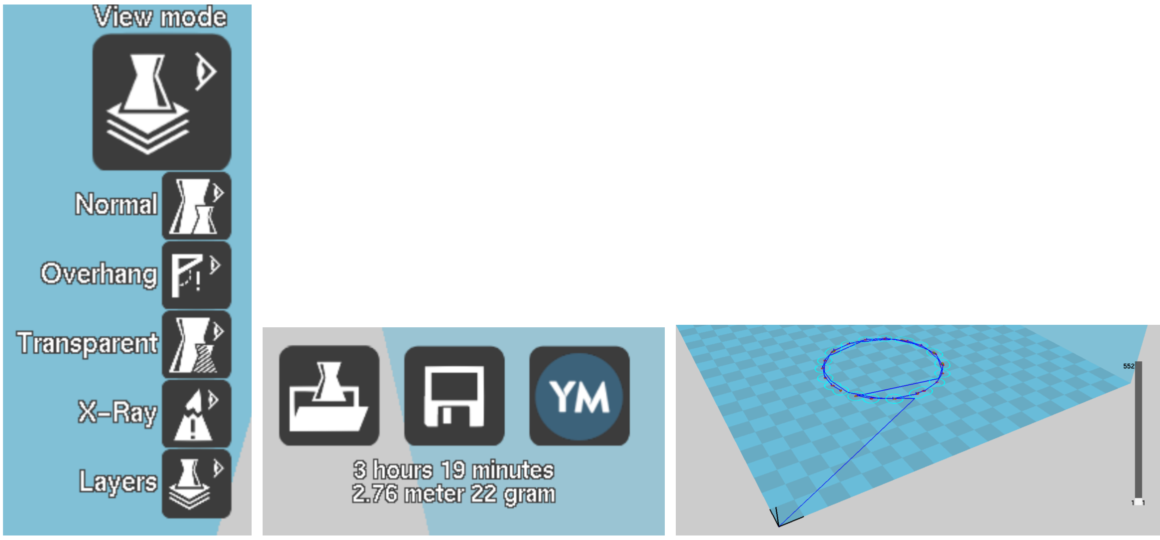
Support type	None
Platform adhesion type	None

Filament

Diameter (mm)	2.85
Flow (%)	100.0

3 hours 19 minutes
2.76 meter 22 gram

Figure 7.1: Layout of Cura



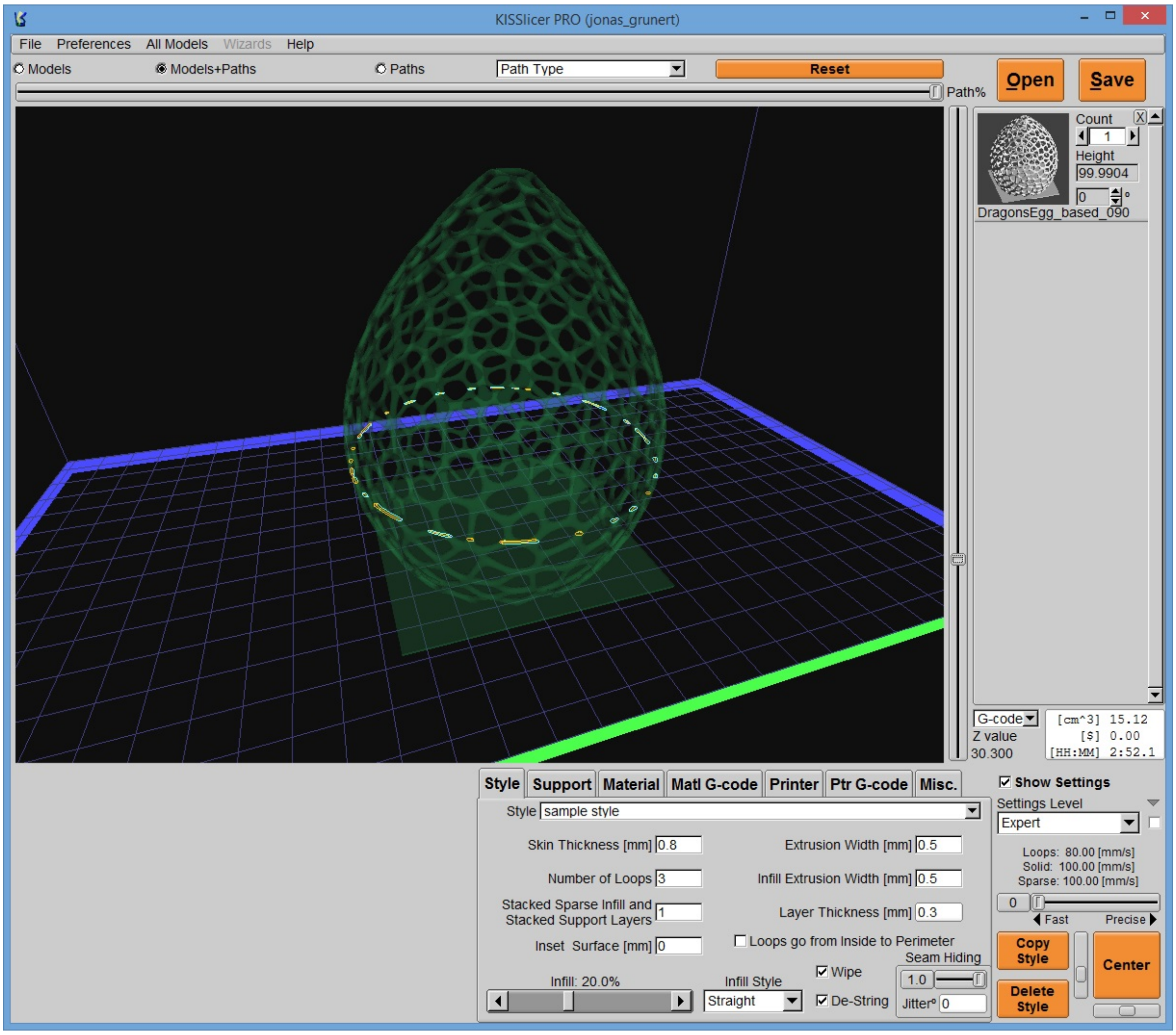
(1) View modes in Cura **(2)** Displayed information in Cura **(3)** Layer view mode in Cura

Figure 7.2: View modes & Layer view mode in Cura

The blue lines in figure 7.2-3 represent the movement of the extruder without extrusion. Cura also calculates the duration of the print, the estimated usage and length of the material (figure 7.2-2).

KISSlicer

KISSlicer has partially a dark and gray theme. The main functions are orange colored so you can easily see them. KISSlicer provides 3 different levels of settings which are *beginner*, *medium* and *expert*. If you select one of these levels or change the current level the user interface refreshes itself directly. So the setting possibilities are limited to the selected level. The *Reset*-Button resets the view to the initial view.
KISSlicer provides three different view modes - 3D model view, 2D G-Code layer view and a combined 3D model and G-Code view.
In the advanced mode KISSlicer offers many detailed settings. It also provides separate profile switching for style, support, material and printer. This is very useful, for example for printing different materials with the same printer.
Some default values are configured poorly for example the extruder speed is to high by default and we had problems with the pre-configured print bed roughness.

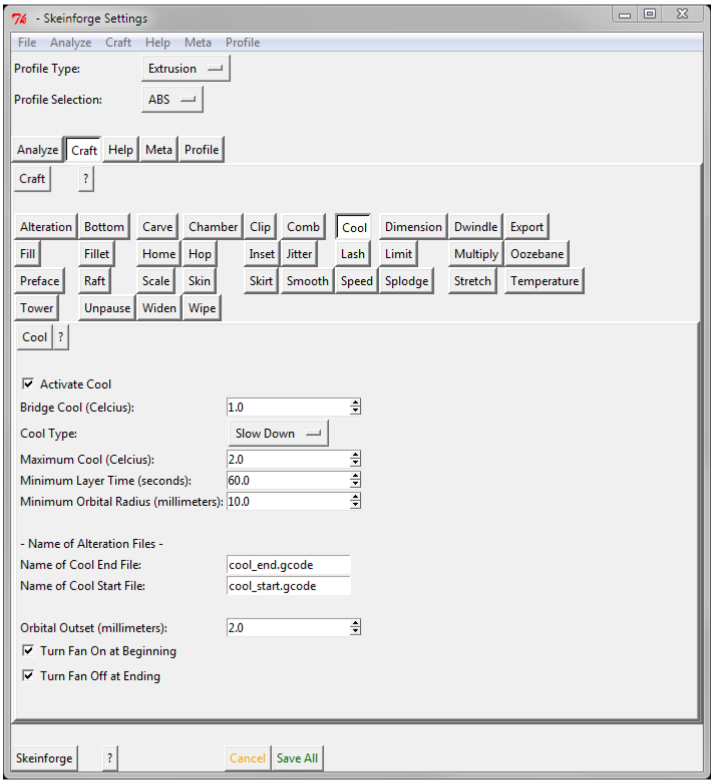


Count 1
Height 99.9904
0 °
DragonsEgg_based_090
G-code
Z value 30.300
[cm^3] 15.12
[$] 0.00
[HH:MM] 2:52.1
☑ Show Settings
Settings Level Expert
Loops: 80.00 [mm/s]
Solid: 100.00 [mm/s]
Sparse: 100.00 [mm/s]
0
Style sample style
Skin Thickness [mm] 0.8
Extrusion Width [mm] 0.5
Number of Loops 3
Infill Extrusion Width [mm] 0.5
Stacked Sparse Infill and Stacked Support Layers 1
Layer Thickness [mm] 0.3
Inset Surface [mm] 0
☐ Loops go from Inside to Perimeter
Seam Hiding 1.0
☑ Wipe
☑ De-String
Jitter° 0
Infill: 20.0%
Infill Style Straight

Figure 7.3: Layout of KISSlicer

Skeinforge

Skeinforge has only a graphical user interface for the settings (figure. 7.4. It provides a command-line-interface which can be used by other tools for example *Repetier-Host* a host software for 3D printer. Skeinforge does not provide separate profiles for different categories but profile switching for all settings.
The strength of Skeinforge is the huge amount of settings which enables advanced users to adapt the slicing process very detailed.



Profile Type: Extrusion
Profile Selection: ABS

☑ Activate Cool
Bridge Cool (Celcius): 1.0
Cool Type: Slow Down
Maximum Cool (Celcius): 2.0
Minimum Layer Time (seconds): 60.0
Minimum Orbital Radius (millimeters): 10.0

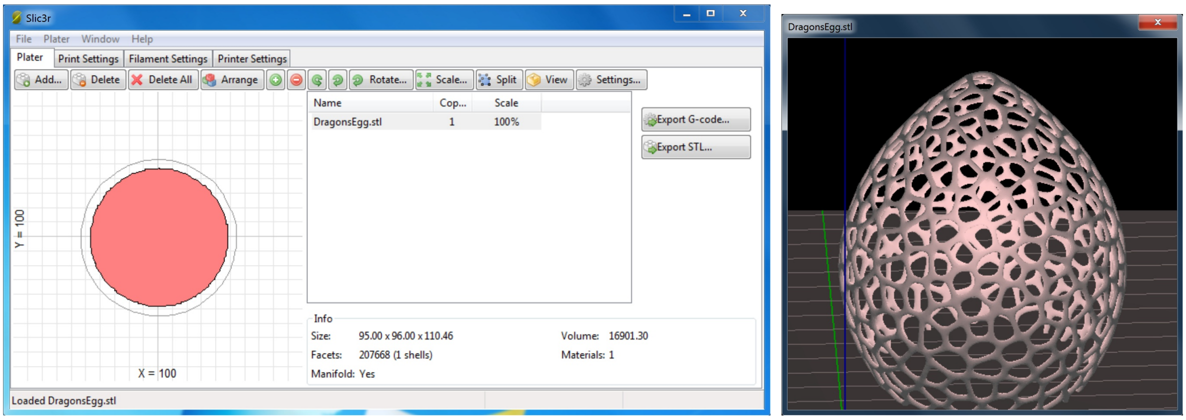
- Name of Alteration Files -
Name of Cool End File: cool_end.gcode
Name of Cool Start File: cool_start.gcode

Orbital Outset (millimeters): 2.0
☑ Turn Fan On at Beginning
☑ Turn Fan Off at Ending

Figure 7.4: Settings screen of Skeinforge

Slic3r

Slic3r has a simple graphical user interface as well as a command-line interface. The view of the model is very limited and the settings are kept simple. The interface is distributed in 4 tabs (figure 7.5-1): *Plater*, *Print Settings*, *Filament Settings* and *Printer Settings*. Editing the model is difficult to get used to because of the complicated adjustment of the buttons. Slic3r provides only a 2D view of the edited or loaded model. There is a button which opens a window to show the model in 3D (figure 7.5-2).
It provides separate profiles for print, material and the printer. In the advanced mode Slic3r offers many detailed settings. There is also a configuration wizard for creating profiles for the most common printers.style, support, material and printer



Name	Cop...	Scale
DragonsEgg.stl	1	100%

Info
Size: 95.00 x 96.00 x 110.46
Volume: 16901.30
Facets: 207668 (1 shells)
Materials: 1
Manifold: Yes

Loaded DragonsEgg.stl

(1) Main screen of Slic3r **(2)** 3D view in Slic3r

Figure 7.5: User interface of Slic3r

7.2 Speed

This section handles about the slicing speed of the slicing tools. First it is necessary to load the model which is mostly saved as a stl-file (see section 2.4) in the slicing tool. After loading the model a profile can be selected or configured to slice the model. As a result of the slicing the G-Code of the loaded model will be saved or generated. The described procedure to slice a model is a common procedure on the used slicing tools except on Cura. Cura slices the model and generates the G-Code of the model directly after loading the model. After changing the profile configurations Cura slices again automatically.

Slicing Dragon's Egg

In table 7.1 are the durations of slicing listed. The durations of slicing the Dragon's Egg are listed in table 7.1. Dragon's Egg is a complex model and it is interesting to see differences between the slicing tools. The fastest slicing tool used for slicing Dragon's Egg and that is used in this work is Cura followed by Slic3r. With a duration of 43 seconds KISSlicer comes third in slicing Dragon's Egg. Skeinforge needs 100 seconds and it is hereby clearly slower than the slicing tools which take the first three places.

	Cura	KISSlicer	Skeinforge	Slic3r
Dragon's Egg	15 sec	43 sec	100 sec	32 sec

Table 7.1: Duration of slicing (mean values)

Chapter 8

Conclusion

In this chapter we will give an overview over this work, summarize the strengths and weaknesses of the slicing tools and give an outlook for future work.

8.1 Synopsis

In the introduction chapter **1.2** we formulated a set of goals and questions to investigate in this work.
We defined formalizations and metrics in Foundations chapter 4 and we tested the reproducibility in chapter 5. Based on this we evaluated the abilities of the slicing tools in chapter 6 and in chapter 7.

We tested the influence of different slicing tools and slicing tool configurations on:

... the quality of the surface of the printed object: In general a thinner layer thickness gives smoother surfaces but to thin layers (<= 0.2mm) can cause warping, especially when printing thin structures.
All slicers have similar smooth surfaces for normal structures but KISSlicer and Slic3r can handle fine structures better.

... the quality of overhangs and bridges: Slicing tools have a huge influence on the quality of overhangs and bridges. Slic3r has a good support for bridging, KISSlicer does not support bridging. Cura had the best results in our Overhang Test.
Cooling the print with a cooling fan can improve the quality of overhangs and bridges significantly.

... the overall precision of the printed shapes and objects: All slicing tools achieved a good print precision for FDM printing, in average a deviation 0.2 mm. Usually the printed parts are bigger than the original model because the molten plastic can deflect. The slicing tools KISSlicer and Slic3r had the best precision in our test model - about 80% of the measurements had a deviation below 5%. In our reproducibility test the deviations were shown to be reproducible.

... the stability of the model: The influence of the slicing tools on the stability is minimal. In our Strain Tests all measurements were similar except the tensile strength test - the strength of the print sliced with Skeinforge was lower.
The biggest influence on the stability is the plastic temperature. When printing to cold the layers don't join properly.

... the general printability of a 3D model: When configured similar the slicing tools achieve the same print bed adhesion.
Prints sliced with Slic3r had the problem that the extrusion nozzle sometimes touched the printed plastic. This can destroy parts of the model or even peel the model off the print bed. The other slicing tools had no such problems.
In general the influence of slicing tools on the printability is moderate.

For this study we have made several assumptions concerning the used FDM printers. All results are depending on these assumptions, described in Section **4.4**. The results may vary under different circumstances.

8.2 Slicing Tool Strengths and Weaknesses

In this section we give an overview over all strengths and weaknesses of all analyzed slicing tools

8.2.1 Cura

Cura is the best choice for beginners or users who want a fast and easy to use slicing tool. The print results are middle-rate, in most of the tests the results were good but not the best ones compared to the other slicing tools.
Cura had good results in the Cup Model **6.4** and the Overhang Test **6.2**. The results in Text Test **6.3** and Precision Test **6.6** were also good but Cura did not slice the very thin structures. Cura hat problems with the fine structures in Fine Pillars Test **6.5** and Dragon's Egg **6.1**.

Strengths:

- Very user-friendly interface
- Very fast slicing
- Good overhang printing
- Provides command line interface

Weaknesses:

- Rougher surface
- Lower print precision
- No advanced settings

8.2.2 KISSlicer

KISSlicer is the best choice for demanding advanced users. It had good print results in many tests but in some situations it has also problems.
It has a graphical user interface with configurable settings complexity but some default values are configured poorly. Therefor KISSlicer is not perfectly beginner friendly.
KISSlicer printed the models Dragon's Egg **6.1**, Text Test **6.3** and Precision Test **6.6** very good and with a high measured precision. The print quality of Fine Pillars Test **6.5** was also good but the thinnest pillars were not sliced. KISSlicer had difficulties with the Overhang Test **6.2** and there was a visible, vertical seam in Cup Model **6.4**. Farer KISSlicer has no support for bridging as shown in Adhesion and Bridging Test **6.7**.
A disadvantage of KISSlicer is that the Pro Version with support for multiple extruders and multiple models is with costs but there is a free version with limitations.

Strengths:

- ◇ Very good print results with fine structures
- ◇ High print precision
- ◇ Separate profiles for style, support, material and printer settings

Weaknesses:

- ◇ Visible seams in some print situations
- ◇ Not slicing very thin structures
- ◇ Some default configurations can cause problems

8.2.3 Skeinforge

Skeinforge is the best choice for users who want a lot of configuration values to configure the slicing. With normal settings the print results of Skeinforge were middle-rate in our tests. The slicing speed was very slow compared to the other slicers.

Skeinforge has no standalone application, slicing is done via command line interface. There is a graphical user interface for the configuration values but it is not as user-friendly as the other slicers.

The results in Text Test **6.3**, Fine Pillars Test **6.5** and Dragon's Egg **6.1** were good but not the best results. There were problems with the retraction, this caused sometimes smearing. In the test Cup Model **6.4** there was also a visible, vertical seam, the same problem as KISSlicer had. Thin structures sliced with Skeinforge can be unstable as the thinnest pillars in Fine Pillars Test and measured in Strain Tests **6.8**.

Strengths:

- ◇ Many detailed configuration values
- ◇ Provides command line interface

Weaknesses:

- ◇ Difficult to get started with
- ◇ User interface not user friendly
- ◇ No standalone application
- ◇ Very slow slicing

8.2.4 Slic3r

Slic3r is the best choice for the average user who wants a free slicing tool. Most of the print results were good and the application is not difficult to use.
Slic3r has a graphical user interface which can be used as standalone application or only for configuration when using it via command line interface. It also offers detailed configuration values and separate profiles for different categories.
The results in Cup Model **6.4** were very good, the handle and the cup surface were very smooth. The results in Dragon's Egg **6.1**, Fine Pillars Test **6.5** and Precision Test **6.6** were also good but showed one weakness of Slic3r: For very thin vertical structures it can happen that the material warps and the extruder nozzle destroys the printed structures. Farer Slic3r has problems with thin diagonal structures as shown in Adhesion and Bridging Test **6.7**.
The default settings for the bottom layer can help dealing with bumpy print beds but it can reduce the adhesion as seen in Adhesion and Bridging Test **6.7**. This behavior can be disabled.

Strengths:

- ◇ High print precision
- ◇ Separate profiles for print, material and printer
- ◇ Configuration wizard
- ◇ Provides command line interface

Weaknesses:

- ◇ Problems with diagonals and very fine structures
- ◇ Thin structures can be destroyed by extruder nozzle
- ◇ Standalone application not user friendly

8.3 Future Work

In our work we focused on comparing slicing tools under same conditions. We did not configure each slicing tool individually to get the best results. This makes the results better comparable but the print results can be improved with better, individual settings.
We also focused on objects that can be sliced without problems. There are differences in handling difficult models which can be investigated.
The results were mainly tested on a RepRap Mendel. There are much more printers to test and the results could be different on other printers.

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Erklärung

Ich versichere, diese Arbeit selbstständig verfasst zu haben. Ich habe keine anderen als die angegebenen Quellen benutzt und alle wörtlich oder sinngemäß aus anderen Werken übernommene Aussagen als solche gekennzeichnet. Weder diese Arbeit noch wesentliche Teile daraus waren bisher Gegenstand eines anderen Prüfungsverfahrens. Ich habe diese Arbeit bisher weder teilweise noch vollständig veröffentlicht. Das elektronische Exemplar stimmt mit allen eingereichten Exemplaren überein.

Ort, Datum, Unterschrift