

Influence of slicing tools on quality of 3D printed parts

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ABSTRACT

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.

The goal of this study is to compare available slicing tools for 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 with appropriate tests and comparisons, and (3) evaluating the slicing tools using the analysis as solid foundation.

KEYWORDS

FDM printing quality assessment; FDM printing quality metric; 3D printing

1. Introduction

3D Printing technique has evolved significantly since its invention in 1989 [6] as well as expanded its use beyond intended purposes (e.g. printing of houses/building blocks [27] printing of medical implants [11] or freeform batteries [13]). Further to its expansion in the professional realm it has also gained traction in the semi-professional and amateur domain [16]. It stands to reason that the success of this technology comes partly because of the widespread adoption in the so called “maker-movement” which results in reduced costs and readily available printers and models. The most widespread class of printers (in semi-professional/amateur terms) are following the Fused-Deposition Modeling technique (FDM, trademarked by Stratasys Ltd [25]) in which molten plastic (mostly ABS and PLA [1]) is extruded through a nozzle building up structures comprised of thin tubular plastic. This technique is also known under the term Fused-Filament-Fabrication (FFF).

One problem common to 3D printing is the step of transforming the blueprint/model into code which can be executed by the printer itself. This step is called slicing because of the slice-wise (in regard to the z-axis of the printer) handling of the data that is to print. In this step the processor/slicer has to determine which machine-paths and (in case of FDM) extrusion speeds are best suited to print an object that most closely resembles the original object or model. These decisions are necessary because physical conditions (flowing material, printing in air, structural strength) restrict viable operations.

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.

With this work we want to showcase a subset of available slicing tools and the associated test set of models as well as methods of testing said tools. Research on assessing the surface quality of FDM printed parts relies heavily on visual inspection as shown by Armillotta [3]. The reader should gain knowledge of parameters within said tools that influence printing quality and understand how and why this is the case. Furthermore we want to provide information on structural features inherent to models that affect the quality of the printed model and the selection of parameters for the processor. A classification of errors usually to be found in FDM printed parts can be found in Mukesh et al. [2]. Our set of test-models and the associated metrics should contribute to achieving a more comparable quality assessment of both slicing tools for FDM printers and FDM printers itself.

Those tests in the current form are intended to be performed manually “ex post” but the further goal is to implement them to be performed automatically so they can be performed whilst printing potentially enabling the in-situ adaption of printing process (active or closed loop printing).

We set ourselves three goals:

- Goal 1: We want to provide consistent and useful metrics in order to formalize the quality impacts that we want to examine. Without applying reproducible and

useful metrics a discussion on quality differences of 3D printed objects is impossible.

- 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.

2. Technology

In this section we explain the printing technology and tool chain we use in our tests. For all our tests we use the technology fused deposition modeling (FDM). This work focuses on printers and slicing tools adapted for Cartesian layouts.

2.1. FDM printing

Fused deposition modeling is a 3D printing technology where molten plastic beads are extruded layer by layer. FDM's most prominent use is Rapid Prototyping [7].

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 [5]. In 2005 the RepRap project was started [19]. 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 (e.g. Makerbot [14] and Ultimaker [29]). 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 use single color printing.

Another 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 focus on the slicing process itself, therefore we do not use support structures in our tests.

2.2. Used printer

All prints are printed with a RepRap-Mendel, iteration 2 [20] printer. The printer is self-built from a kit and is based on the Open Source blueprints developed by the RepRap project [19].

The printer has a simple but solid design of threaded rods and printed plastic parts. The material is printed with a dual extruder for 3.0 mm plastic filament through a 0.5 mm nozzle. Furthermore the printer has a heated print bed and a fan for print cooling.

2.3. Used material

For all tests we use ABS (Acrylonitrile butadiene styrene) thermoplastic filament. All tests are printed with red ABS filament with a diameter of 3.0 mm. All material that we use originates from the same manufacturer.

2.4. File formats

Usually there are two file formats use for printing:

- The input file representing the three dimensional model to be printed
- 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) [23] - 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 others based on its design use G-Code files as printer control files. These 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 (e.g. to STL)
- Calculating the printer tool paths based on the three dimensional model and exporting it (e.g. to G-Code)
- Printing, based on the control file

The process of calculating the printer tool paths based on the three-dimensional model file is called slicing. This is done by separate tools, so called slicing tools.

To calculate these printer tool paths the slicing tools tries to find all solid shapes of the model. Therefore the model has to be manifold, otherwise the slicing tool cannot find the solid bodies. Good slicing tools can try to repair the model if it is not manifold.

The solid shapes are then cut into layers, as thick as the layer height of the printer. Now on every layer the necessary two-dimensional tool paths to print this layer are calculated. This includes the movement on two axes and the feed rate of the extruder. Later the printer will print layer after layer two-dimensionally and move in the third dimension between the layers by the given layer height.

There are various slicing tools with different advantages and disadvantages. The quality of the slicing can have a huge impact on the printing result.

A good slicing tool should not only calculate each layer separately but also look into the layers above and below. When dealing with overhangs and complicated structures the slicing tools can improve the print result a lot this way. As we could see in the produced G-Code the printhead was accelerated in areas where an overhang was detected and while bridging. Another reason indicating this behavior was seen as the start of a new layer was not put into the air but on existing material. Indication for looking above was found when analyzing the G-Code structure for infill patterns where the slicer looked a few layers ahead to adapt the infill pattern (closing the pattern for more stability).

This case study's main focus is to show the difference between slicing tools and how they affect the printing quality.

3. Slicing tools

As mentioned in Section 2.5 - 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.

In this section we present the slicing tools we selected for the tests and the selection criteria.

Besides the slicing tools abilities their configuration also has a huge impact on the quality. In the section slicing tool configuration (3.4) we explain the settings we use for our tests. For better comparability we use the same settings for all tests and slicing tools.

All settings are optimized for our 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

Under the assumption, that the number of hits for a slicing tool in popular search engines is associated with the popularity, the following packages belong to the most popular slicing tools (as of May 2014):

- Cura, 14.03 (open source project by Ultimaker) [30]
- KISSlicer, 1.1.0.14 (commercial project) [12]
- Skeinforge, Release 50 (open source project) [22]

- Slic3r, 1.0.0 RC3 (open source project) [22]
- RepSnapper, 2.2.0 b3 (open source project) [18]
- Miracle-Grue/Makerware, 2.4.1.62 (freeware project by Makerbot) [15]

3.2. Selection criteria

From the available slicing tools found we use 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 it can be printed with the 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 configure all slicing tools with the same configuration values.

3.3. Excluded slicing-tools

3.3.1. Miracle-Grue/Makerware

The G-Code generated with Miracle-Grue was not compatible with our RepRap-Mendel printer. Therefore we had to exclude it was not possible to compare the results with the other slicing tools on our RepRap printer.

3.3.2. RepSnapper

RepSnapper was excluded because it did not work reliably. When slicing the model DragonsEgg the slicer crashed repeatedly. When slicing the model TextTest not all parts of the model were sliced. RepSnapper is in an early development beta state [21]. 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 are analyzed and described: Cura, KISSlicer, Skeinforge and Slic3r. The other tools are excluded due to their lack to fulfill the selection criteria.

3.4.1. Cura

Cura the open source software developed by Ultimaker includes everything to prepare a 3D file for printing and slicing it. It is available on Linux, Mac and Windows.

Multiple industry-standard files like STL, 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 6.2.

3.4.2. 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 files.

KISSlicer is available on FreeBSD, Linux, Mac and Windows. One can use KISSlicer in different languages. KISSlicer has a gray theme with orange-colored buttons.

KISSlicer is presented in detail in section 6.3.

3.4.3. Skeinforge

Skeinforge is a 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), G-Code 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 6.4.

3.4.4. Slic3r

Slic3r converts STL, OBJ and AMF 3D models into G-Code instructions.

It is available on Linux, Mac and Windows. Additionally Slic3r can be used from the command line. 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 software.

Slic3r is presented in detail in section 6.5.

3.5. Slicing tool configuration

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

3.5.1. General settings

- Travel Speed - Speed of the extrusion head when not printing: 150 mm/s

- Bottom Layer Speed - Speed of the first layer on the print bed: 20 mm/s
- Shell/Perimeter Speed - Speed of the perimeters: 30 mm/s
- Infill Speed - Speed for internal fill: 45 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: 20 s
- Fill density - Percentage of fill density for inner beads: 20%
- Fill pattern - Pattern how to do infill: Rectilinear
- Printing temperature - Temperature of the plastic extruder: 250 °C
- Bed temperature - Temperature of the print bed: 110°C

3.5.2. Layer settings

For the tests we use three different layer thicknesses. For every model we try out different layer thicknesses and choose 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 fewer errors.
- 0.4 mm for models with overhang. The surface is rougher but there are fewer errors at overhangs.

3.5.3. Support structures

In all tests we print without support structures. Our main goal is 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.

3.5.4. Advanced settings

Most of the other setting values are 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 keep the default values in order to harness possible internal slicer optimization.

Slicer software is expected to have well-adjusted default settings in order to enable novice users printing desired results.

We enable retraction (pulling back the filament when traveling) for all slicing tools.

4. Foundations

In this section we present the criteria and metrics we use to compare slicing tools and printed results. All used specimens have been made public by the respective authors for further research. For further information see the given references.

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 describe the deviations that commonly occur throughout our study and how we quantify them.

4.1.1. Overhangs and bridges

We define overhangs as extruded material without supporting structures right underneath. Overhangs are generally attached to existing structures (we do not print 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.

4.1.2. 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 remains

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 can 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 then removing the plastic remain will 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.

4.1.3. 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 one of the main strength problems 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 too hot also can cause problems with warping or burned material so there is a temperature limit.

When printing too fast the plastic cannot lie down properly and the strength also suffers. However a problem with printing too slow is that the material cools down and the issues with printing too cold mentioned above occur. In our tests we print with 25 mm/s print speed and 250 °C extruder temperature.

4.2. Metrics

In order to quantify and compare the quality impacts mentioned in the last section we have developed the following metrics. This section gives an overview on the metrics we use and how we measure 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 0.01 mm, as shown in Table 1.

4.2.2. Metric for text quality

In our tests for printing text we print lines with decreasing letter size for testing how small letters the slicing tools can

Table 1. Metric used for measuring model deviations.

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

render. We rate all lines separately. For each line use the following ratings (See Table 2.):

Table 2. Metric used for measuring text print quality.

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

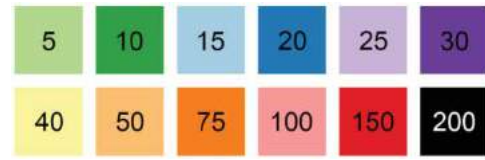
For testing how reproducible the test results are we print one of our test models twice under the same conditions - same model, same G-Code, same printer and same ambient temperature (25°C).

As test model we use the model Precision Test (See Section 5.3). This model has various difficulties like thin structures, holes and bridges. We use KISSlicer for slicing and the same settings as in Section 5.3.

We measure the difference between both prints. The average difference between the two prints is 0.03 mm or 0.59% relative to the measured length.

4.3. G-Code viewer

In order to analyze the various G-Codes produced throughout this study we have extended the gCode-Viewer [31] by Alex Ustyantsev for this problem. 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 speed in millimeters per second. The color legend is thus the

**Figure 1.** Color legend of all G-Code figures in this study. Extrusion speeds are measured in mm/s.

same for all G-Codes throughout this study and is shown in Fig. 1.

5. Evaluation

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

5.1. Overhang test

The first model is the Overhang Test model [10]. As the name suggests, this is a model created 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 choose this model for this study as we experienced different qualities of the printed overhangs in pre-tests. 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 examine the influence a cooling fan has on the quality of the printed model.

5.1.1. Comparison of overhang test with and without fan cooling

We use 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 3.

Table 3. Results from overhang printing test.

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

In general the version without the use of a cooling fan (Fig. 2-a - 2-d) is of lower quality than the same versions that are cooled during printing (Fig. 2-e - 2-h). Nevertheless the overhangs with 45° and 40° can be printed with good quality regardless of fan cooling. Overhangs with 35° and 30° can 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 (Fig. 2-i) uses the slowest extrusion speed with ~ 15 mm/s and has the best result. KISSlicer, Skeinforge and Slic3r mainly extrude with ~ 20 mm/s but Slic3r speeds up to ~ 30 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

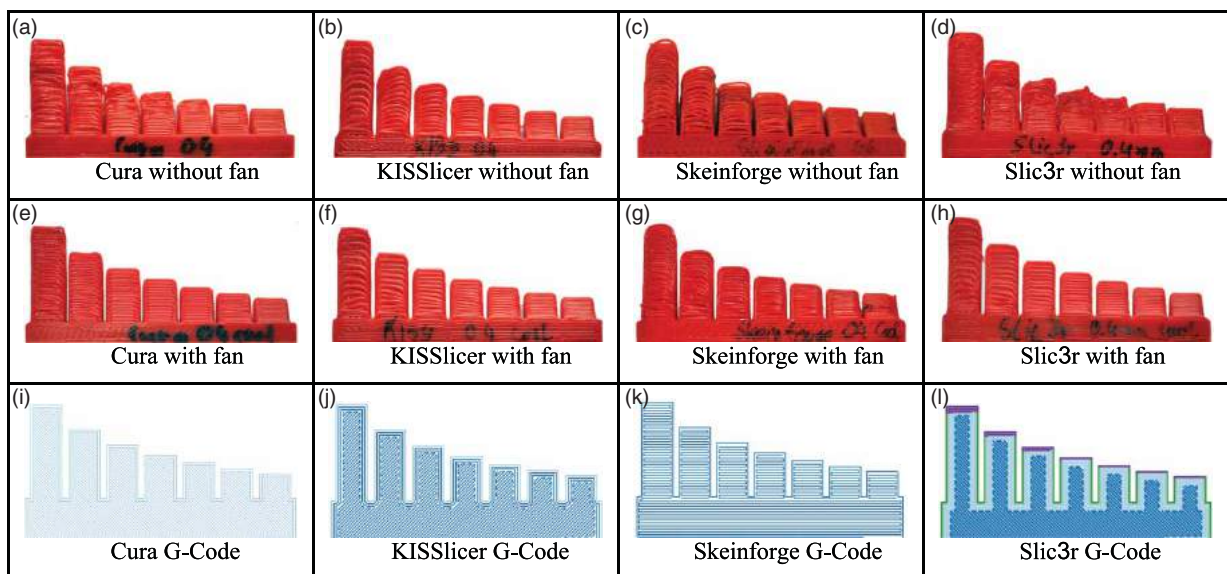
top starting with ~ 10 mm/s and reaching ~ 25 mm/s in the top layers. In addition to that the corners of the overhangs become increasingly rounded the higher the extrusion speed becomes.

5.2. Text test

The Text Test model [8] 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. For further measurement see Fig. 10 (Appendix). The font used is the default font of Blender [4] by the name of “bfont”.

Letters have been chosen as letters have a very high level of detail with uncommon geometric forms. They are commonly printed as very thin walls with a small height. The thin wall is difficult to print, as the walls may face in any direction or may be even curved. At the time of writing approximately a third of the 100 most popular models (measured by “likes”) on Thingiverse [28] contain small decorative structures or letters. It is thus of high interest to ensure visually appealing prints even with such a high level of detail. For this study we chose letters as fine-grained structure and leveraged the readability as quality indicator. 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.

**Figure 2.** Erroneous parts of the Overhang Test model with different slicing tools- with fan cooling and without fan cooling.

Other difficult areas 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.

5.2.1. Comparing text test with different slicers

We use all available slicing tools to print the Text Test model. The exact settings are listed in Table 4.

As seen in Fig. 3 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

Table 4. Observed results for Text Test.

Slicing tool	Nozzle	Layer Thickness	Observations
Cura	0.5 mm	0.3 mm	The first four lines are readable. The fifth line is unreadable and all further lines are not being printed.
KISSlicer	0.5 mm	0.3 mm	The first four lines are readable. It is possible to identify the location of the fifth to the tenth line, but the characters cannot at all be identified in those lines.
Skeinforge	0.5 mm	0.3 mm	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	0.5 mm	0.3 mm	The characters of the first five lines can be identified. From the sixth to the eighth line only some of the letters can be identified. In the ninth and tenth line no letter can be identified.

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 Fig. 4. 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

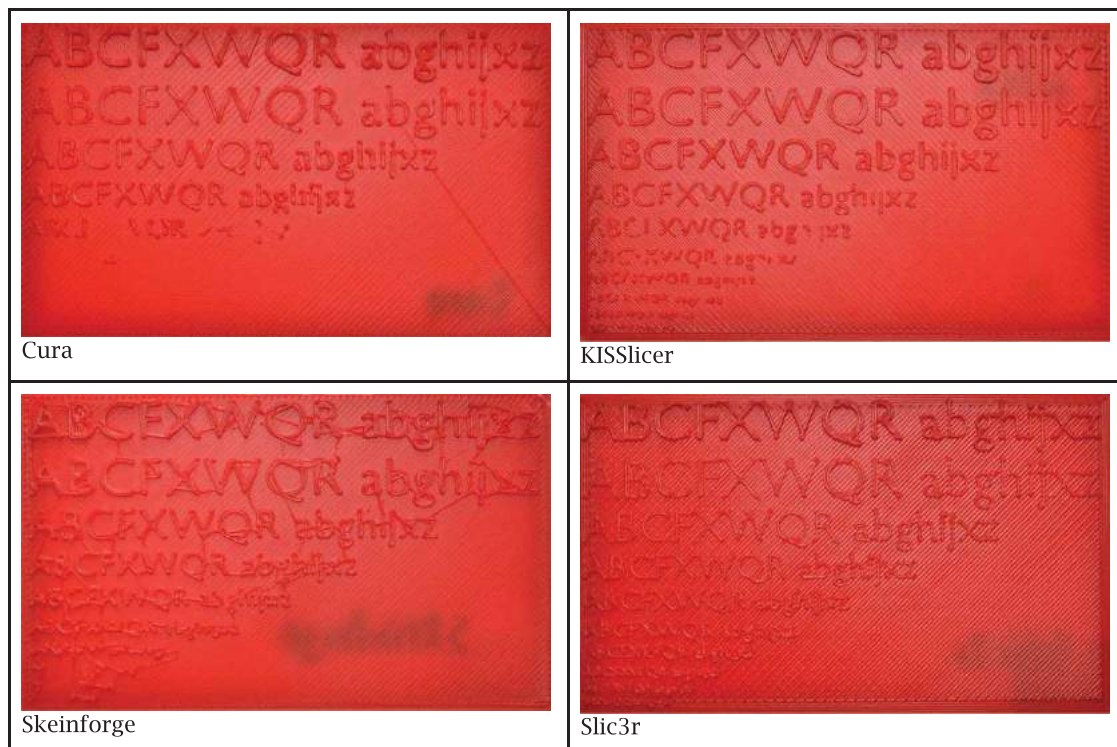


Figure 3. All results of the Text Test model.

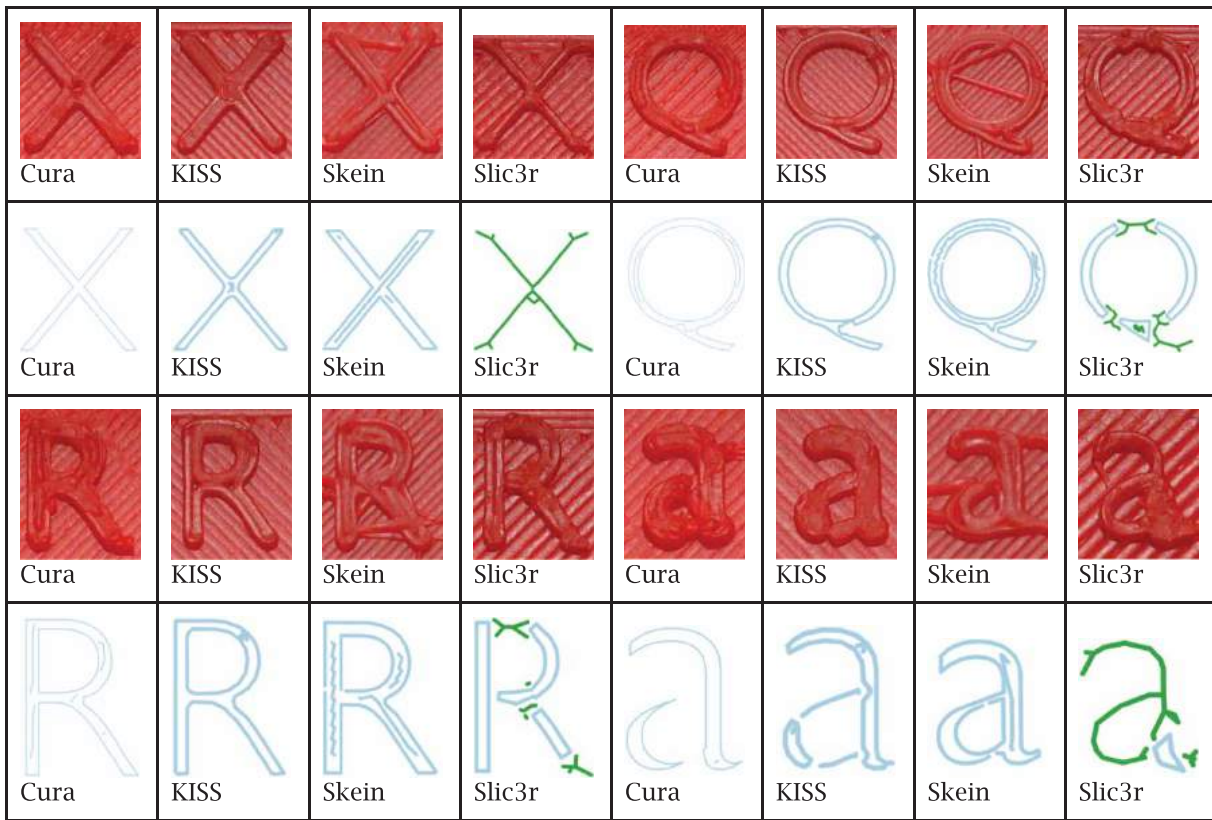


Figure 4. Selected letters of the Text Test with corresponding G-Codes. Used abbreviations: KISS: KISSlicer, Skein: Skeinforge.

Table 5. Detected letters of Text Test using OCR (Detected letters out of the total number of letters per line).

Slicer	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6	Line 7
Cura	15/16	16/16	13/16	13/16	0/16	0/16	0/16
KISSlicer	15/16	16/16	16/16	14/16	6/16	0/16	0/16
Slic3r	12/16	14/16	15/16	13/16	8/16	6/16	0/16
Skeinforge	0/16	0/16	0/16	0/16	0/16	0/16	0/16

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 an X-like extrusion pattern.

Additional to the visual inspection and quality assessment of the Text Test we devise a method to assess the quality automatically and reproducibly by coloring the letters using a black colored marker, photographing (see Appendix Fig. 12) the plates in diffuse daylight at a distance of 12 cm and using OCR to detect the letters. For character recognition we use Tesseract [26] OCR version 3.02. Before the OCR step we post-process the pictures using Paint.NET [17] to increase the saturation to 150, the contrast by 80 and the brightness by 80 and to filter noise pixels using a threshold (Appendix Fig. 13). The following table (Table 5) displays the result of this automated letter detection.

5.3. Precision test

Using the knowledge gathered in the previous models, we develop a custom model to test all difficulties in parameterized varieties. The Precision Test model (Fig. 5)[9] is used to test small and fragile geometric objects and bridges.

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 5.

In order to analyze this model we use a digital caliper to measure a selected set of objects. The chosen locations are shown in Fig. 5 and the respective results are listed in Table 6.

All slicing tools print the measured pillars 04 and 05 up to 1 mm 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 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.

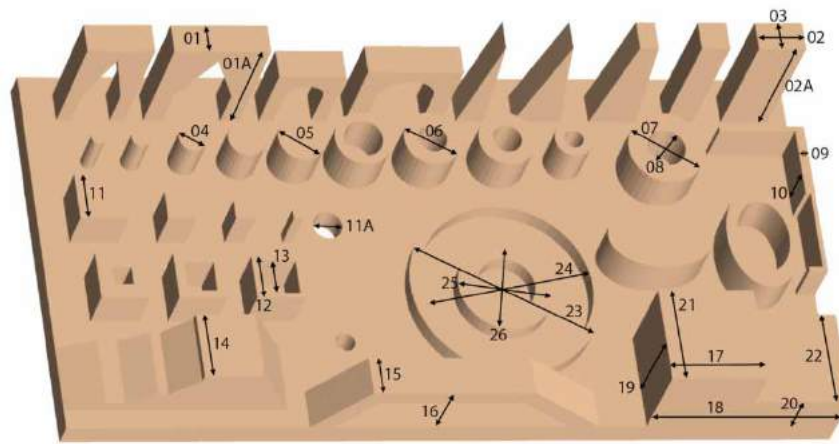


Figure 5. Locations measured with the caliper in Precision Test.

Table 6. Slicing tool settings and observed results for Precision Test with different slicing tools.

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

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 Fig. 7) 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 1 mm 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 Fig. 6 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 Fig. 6-a - 6-d. The slicing tools also apply different slicing techniques while extruding the infill around the holes as seen in Fig. 6-e - 6-h. However, the approaches seen in Fig. 6-i - 6-l are the approaches that are used to extrude the surfacing layer around the hole and thus the visible ones. The printed holes are shown in Fig. 9. Cura's technique is very good as the area around the holes is 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 visible very well and have a slightly rough surface. Skeinforge extrudes 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 Fig. 9) 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 Table 7, measurement 10) is very accurate amongst all slicing tools. However the width of the wall varies up to 50% (compare Table 7, measurement 09) with Skeinforge having the biggest deviation of 0.47 mm and Slic3r

Table 7. Results of the measurement of Precision Test with the caliper.

	Reference	KISS			Slic3r			Cura			Skeinforge		
	absolute	absolute	deviation	deviation	absolute	deviation	deviation	absolute	deviation	deviation	absolute	deviation	deviation
Index	[mm]	[mm]	[mm]	[%]	[mm]	[mm]	[%]	[mm]	[mm]	[%]	[mm]	[mm]	[%]
01	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%
02	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%
03	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%
04	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%
05	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%
06	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%
07	8,00	7,80	0,20	2,5%	8,15	0,15	1,90%	8,07	0,07	0,9%	8,11	0,11	1,4%
08	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%
09	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%

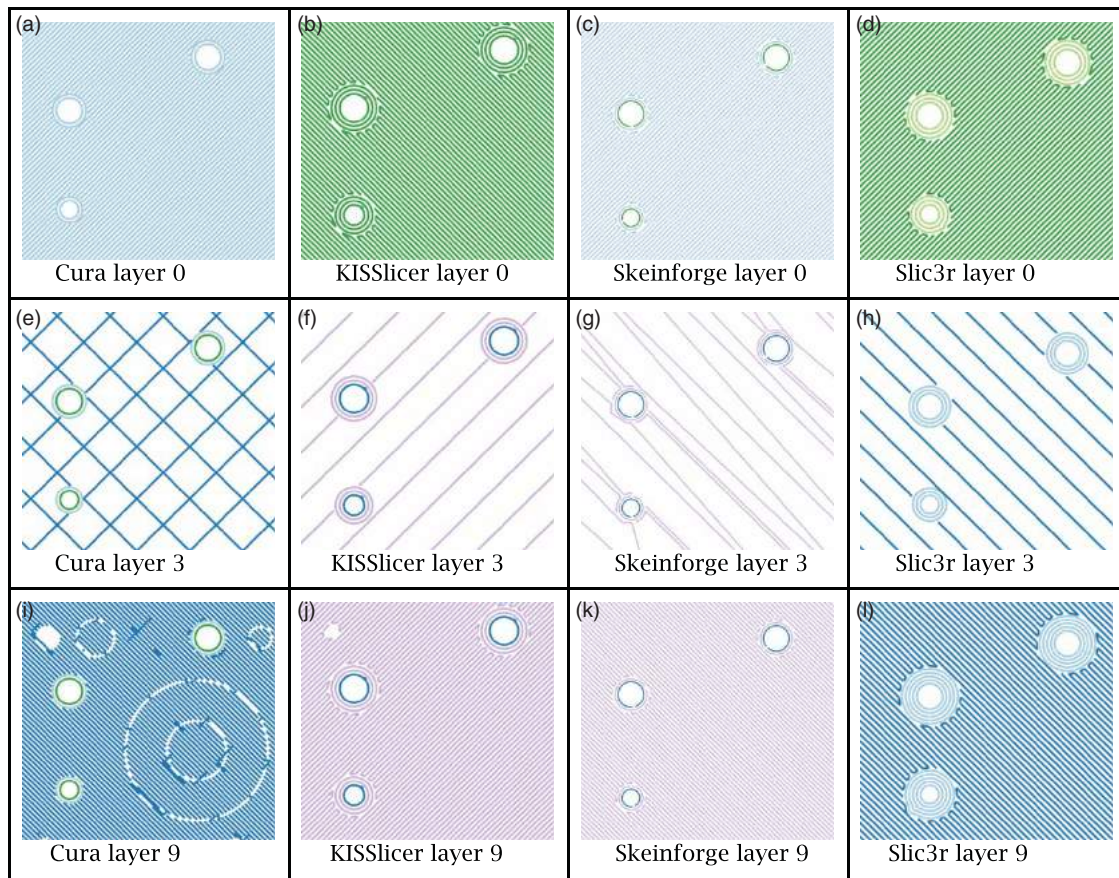


Figure 6. G-Code snippets of the holes in the ground plate for the Precision Test model in different layers.

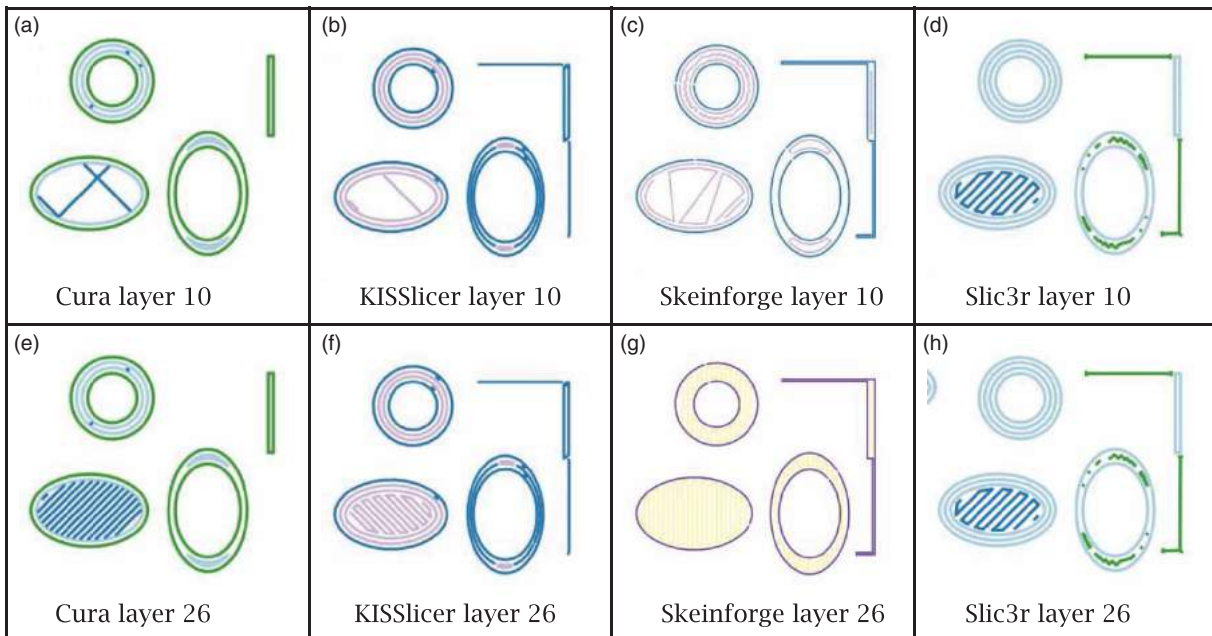


Figure 7. G-Code snippets of the oval pillars for the Precision Test model in different layers.





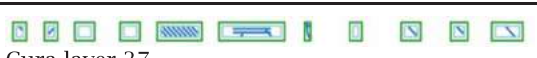
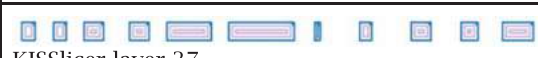






 Cura layer 10	 KISSlicer layer 10
 Cura layer 36	 KISSlicer layer 36
 Cura layer 37	 KISSlicer layer 37
 Skeinforge layer 10	 Slic3r layer 10
 Skeinforge layer 36	 Slic3r layer 36
 Skeinforge layer 37	 Slic3r layer 37

Figure 8. G-Code snippets of the pillars for the Precision Test model in different layers.

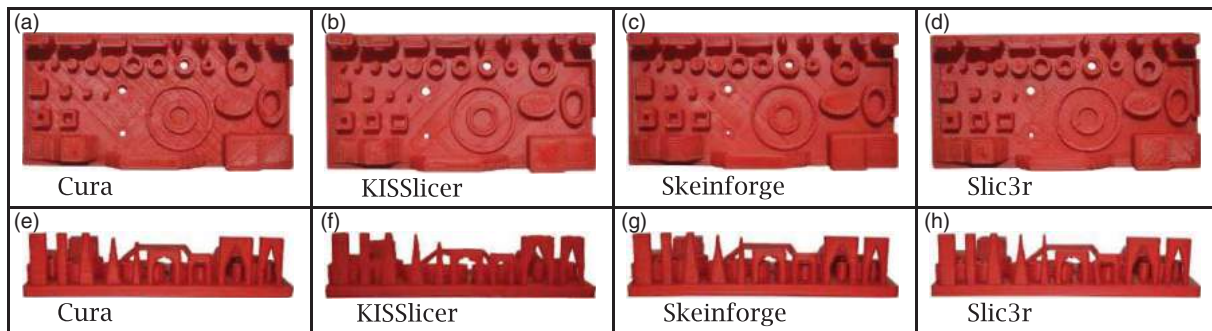


Figure 9. The Precision Test model photographed from the top and from the side.

having the smallest deviation of 0.21 mm. The huge deviation of Skeinforge can be explained by looking at the G-Code in Fig. 7-c as Skeinforge extrudes an infill into the wall whereas the others do not.

Comparing the G-Codes of the hollow ovals in Fig. 7 there is a slight difference between 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 patterns of Cura and Slic3r (Fig. 9-a and Fig. 9-d) lead to little visible holes in the surface whereas the more dense infill patterns applied by KISSlicer and Skeinforge do not produce holes (compare to Fig. 9-b and Fig. 9-c).

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 Fig. 7 it is not possible to identify quality impacts either in shape precision, surface roughness or the actual size.

In this section we examine the impact of the different slicing techniques on the pillars and arcs. The printed results are shown in Fig. 9-e – 9-h with the corresponding G-Codes in Fig. 8. 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 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 Fig. 8 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 mm/s and Slic3r extrudes at 25 mm/s.

Major difficulties for the slicing tools are the triangular towers which resulted in very different heights as seen in Fig. 9-e – 9-h. 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 Fig. 9-h).

6. Usability

6.1. User interface and configuration

This section analyses the user experience of the slicing tools – the user interface and the performance. The different slicing tools are executable applications – executable as command line application and/or as standalone application.

6.2. Usability of cura

Cura has a well-arranged 2-column layout. 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*. If you select the *Layers* view mode you can see the movement lines of the extruder for each layer of the model.

Cura offers a medium amount of settings. There are less settings available 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 files.

6.3. Usability of 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 too high by default and we had problems with the pre-configured print bed roughness.

6.4. Usability of Skeinforge

Skeinforge has only a graphical user interface for the settings. 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.

6.5. Usability of 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: *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.

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.

6.6. Slicing speed

This section examines 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.

Listed below are the durations of a slicing process of a complex model. The test model, by the name of “Dragons Egg” [24], is a complex model with more than 100.000 vertices and 200.000 faces.

- Cura: 15 seconds
- Slic3r: 32 seconds
- KISSlicer: 43 seconds
- Skeinforge: 100 seconds

7. Conclusion

In the introduction (Section 1) we formulated a set of goals and questions to investigate in this work.

We defined formalizations and metrics in Foundations (Section 4) and we tested the reproducibility in section 4.3. Based on this we evaluated the abilities of the slicing tools in section 5 and in section 6.

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

- All slicers have similar smooth surfaces for normal structures but KISSlicer and Slic3r can handle fine structures better.
- The quality of overhangs and bridges. We found that 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 (See Appendix Fig. 11). Another finding is that 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. The findings are that all slicing tools achieved a good print precision for FDM printing; with an average deviation of 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 results may vary under different circumstances like humidity, ambient temperature and other factors. It needs to be shown that these ambient factors do influence printing quality in any significant way.

7.1. Future work

Due to our findings we propose future work to move into the direction of formalizing and standardizing metrics for print quality of FDM printers in order to make it easier and more replicable to compare a) Printers, b) Associated tools/software and c) Printed models. In this area, hard to ascertain features like surface quality or surface roughness are still, like many other features, best assessed by human beings without proper comparability.

Future work could include automated testing for quality assessment of said features in order to provide faster and more exact results. This study reveals certain measurement techniques that can be used as a starting point for future work, although future work should also consider other quality aspects of 3D printed objects. It is important that for various different quality goals (e.g. surface roughness, deviation from original model, stability) metrics exist that can improve the respective quality goal either before printing or measure it after printing.

The focus of this study is on the latter and our results may be used to develop metrics that can be applied before printing to assess that a G-Code has no obvious faults that lead to a bad print result. In our work we focus on comparing slicing tools under the same conditions. We do 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. Research should focus on the ability to preset optimal settings in slicing tools for specific models based on analysis of said models where it has been proven that certain (temporary) settings yield better quality results. The results of analyzing models beforehand should be regarded as suggested print settings with the possibility of changing the settings in case an expert user knows better than the analytical algorithm or in case of errors of said algorithm. We also focus on objects that can be sliced without problems. There are differences in handling difficult models which should be further investigated.

The results are mainly tested on a RepRap Mendel printer but there are many more printers to be tested and the results could be different on other printers.

The detected problem of printed parts being larger than originally modeled should be examined further in order to express a correlation between model and printed object. If this can be formalized it would be possible to be implemented in modeling/slicing software to achieve prints that fit the model better, which would increase the interoperability of printed parts.

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Appendix

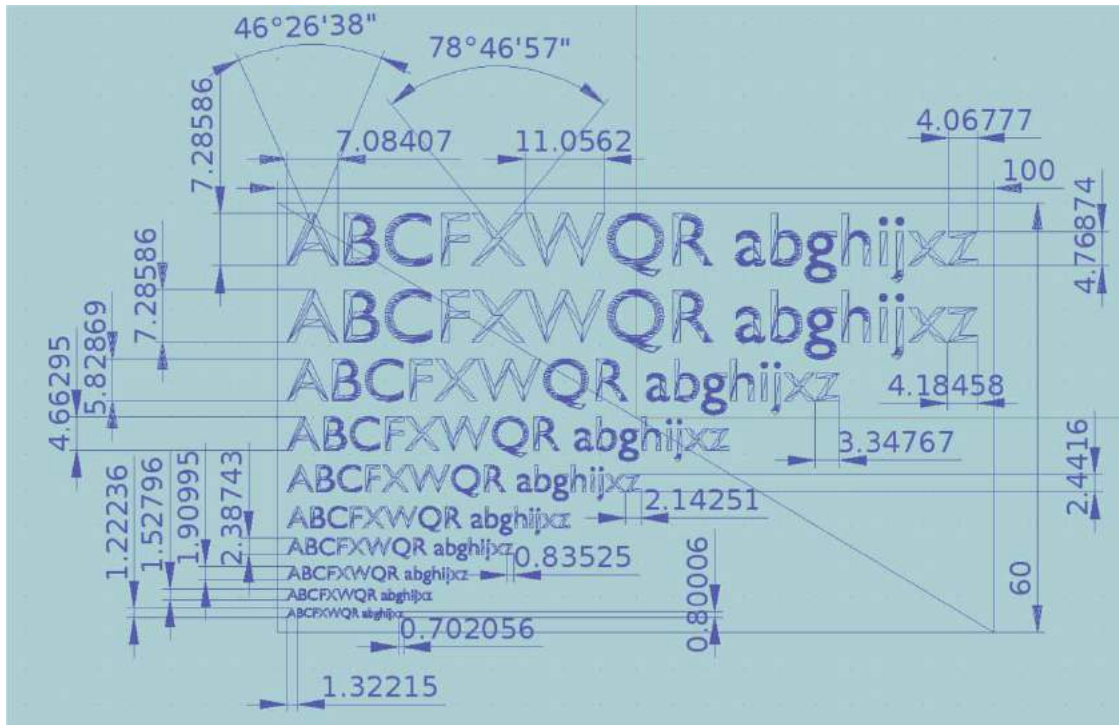


Figure 10. Measurement of Test Text (in mm).

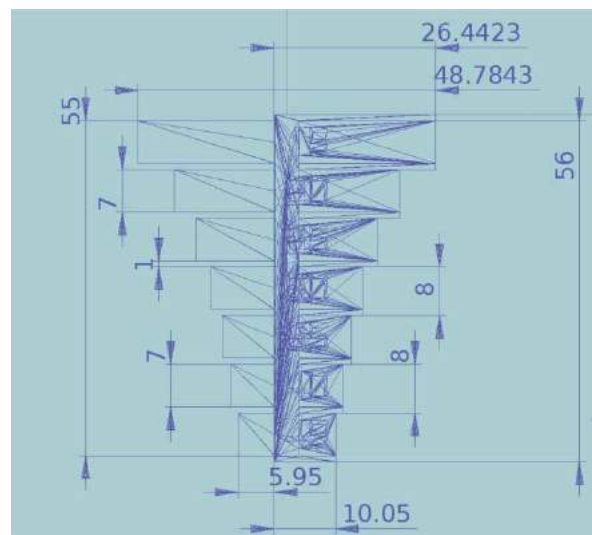


Figure 11. Measurement of Overhang Test (in mm)

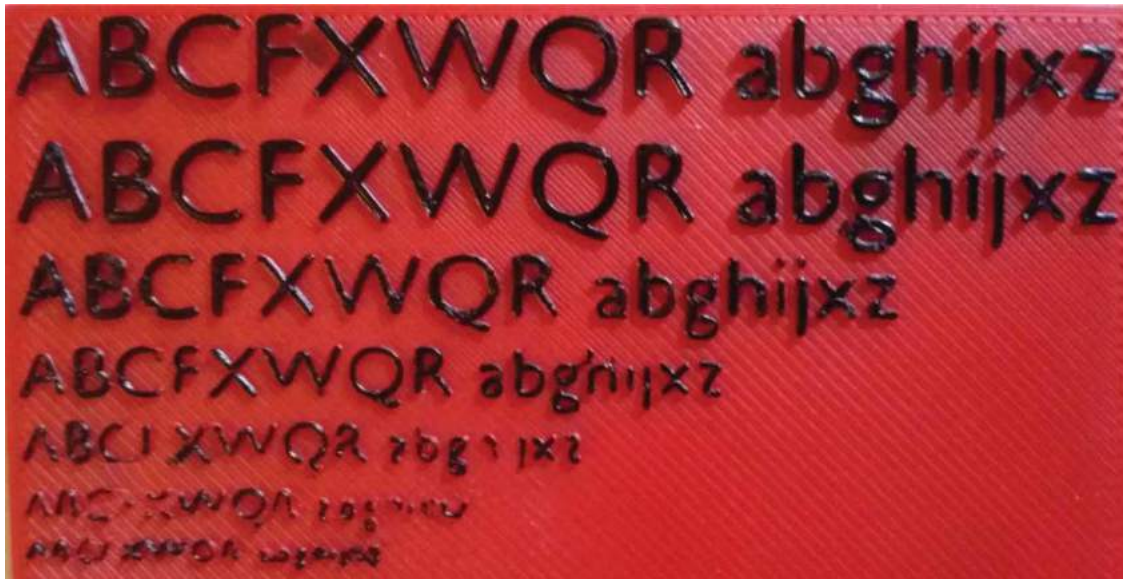


Figure 12. Picture of Text Test model with colored letters (KISSlicer).

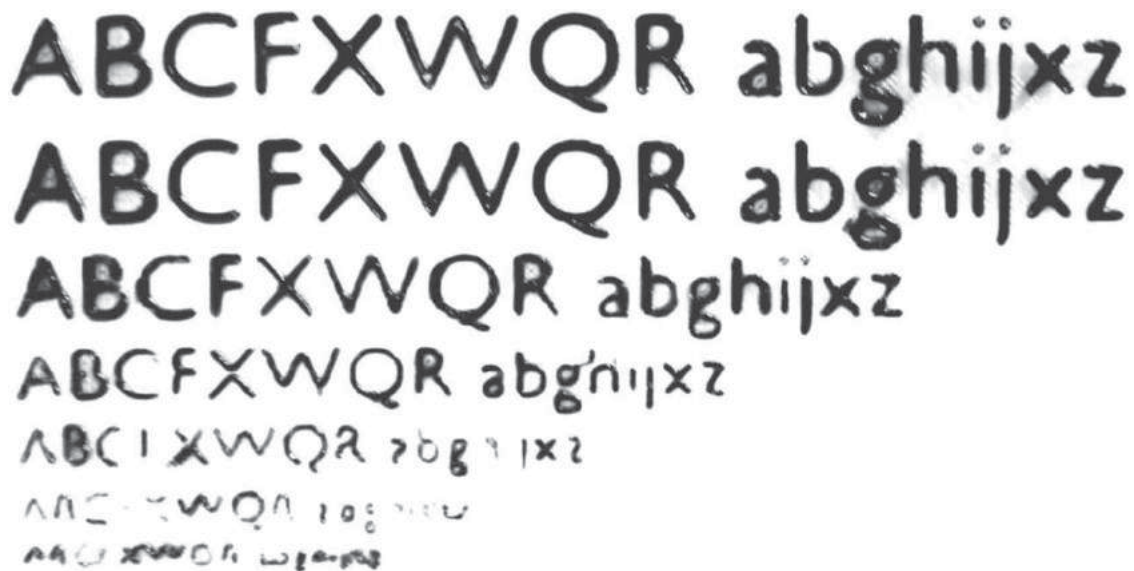


Figure 13. Post processed picture of Text Test model used for OCR.