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INFLUENCE OF SLICING TOOLS ON DIMENSIONAL ACCURACY OF 3D PRINTED MODELS

BY

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Abstract. Nowadays, Fused Filament Fabrication offers many possibilities concerning the manufacturing of parts, based on 3D data. For obtaining qualitative models, there is imperatively a compelling configuration of the slicing tools, and this can differ depending on the used equipment and even the raw material. The purpose of a slicing tool is to convert the 3D data in a set of information that the 3D printer can read and run. By default, the slicing tools come with many options regarding the G-code instructions, and by this, they have direct influence under the quality and dimensional accuracy of the resulted parts. Taking into consideration the great variety of variables that can affect this process and impact under the quality of the resulting parts, the main goal of this study was to verify the influence of the slicing tools, over the dimensional accuracy of the printed models. There was find that each slicing tool has a distinct way to generate the G-code instructions resulting in samples with different levels of precision.

Keywords: fused filament fabrication; parameters; deviations; dimensional accuracy; deviation; gaps.

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1. Introduction

The Fused Deposition Modeling was developed by S. Chump at the end of the '80s and patented in the '90s by Stratasys (Gregurić, 2018). Due to the development of the RepRap project and the idea to develop a low-cost FFF 3D printer (Rhys *et al*., 2011), today there is a large variety of RepRap like equipment, form industrial to desktop size.

The manufacturing process through Fused Filament Fabrication - FFF is a conventional extrusion process implemented on a 3 axis CNC machine (Fig. 1). The raw material, a wire plastic it is forced into a heated nozzle following to be deposited layer by layer until the end of the process. The most common configuration is that in which the extruder system is traveling across XY directions, while the building platform is moving down after each completed layer. The process has many factors that can influence the final quality of the model, but if it successfully controlled, it presents great potential in manufacturing. Even so, the FFF process is similar to other additive manufacturing technologies because it's creating the model layer by layer, is different because the raw material it's forced through a nozzle under constant pressure and specific temperature of the raw material. The pressure and the flow rate of the filament must be kept at constant values to ensure precise results of the manufacturing process (Gibson *et al*., 2015). The main goal of this study is to verify which from the chosen slicing tools gives the best dimensional accuracy, without advanced parameterization. The main goal of this study is to verify which from the chosen slicing tools gives the best dimensional accuracy, without advanced parameterization. For this reason, the following objectives have established as follows:

1. To obtain excellent repeatability of the manufactured models.
2. To use consistent specimens to provide the information needed to compare the slicing tools.
3. To deliver a set of models that give enough information about the dimensional accuracy of small size features.

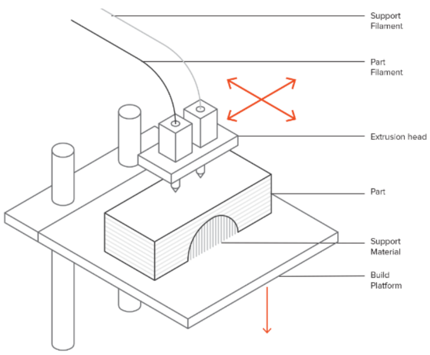


Fig. 1 – FDM 3D printer scheme (Redwood *et al*., 2017).

2. Equipment and Tools

The types of equipment available for this study described below are a three-dimensional printer and measuring devices.

The Printing Equipment is the Prusa i3 Mk3 (Fig. 2), a 3D printer that is using a cartesian system, with a medium building volume of 210 x 250 x 210 mm, with a and dimensional accuracy of ± 10 μm along with XY-directions, and ± 5 μm across z-direction. This equipment is provided with an extrusion system for 1.75 mm filament and can operate in optimum condition upon the temperature of 290^{o}C, and the heating bed works at a maximum temperature of 120^{o}C.

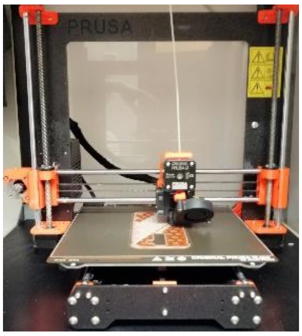


Fig. 2 – Prusa i3Mk3.

The deviation from the nominal values had measured using an Absolute AOS 500 160 230 caliper from Mitutoyo, with a precision of 0.02 mm for values between 0-150 mm and a precision of 0.03 mm for dimensions between 150-200 mm (Mitutoyo, 2019). For providing objective measuring results, a special USB adaptor has used, which is allowing the direct transfer of the measured features into an Excel file.

For all tests, we used PLA (polylactic acid), thermoplastic material with excellent printing properties. All models had manufactured using spools of filament with a nominal diameter of 1.75 mm and a precision of ± 0.02 mm. The average dimension is 1.76 mm. All filaments are from the same manufacturer, to ensure the same characteristics for the raw material.

3. Slicing Tools and Parameterization

The files that are containing the 3D CAD data are regularly an STL file. The STL file composed of an irregular set of triangles without any topological information. Except for the orientation of the triangles. For this study, we used the ASCII type of representation.

The slicing tools are computing the optimum path for the extrusion head and are taking into consideration the data collected from the additive manufacturing file. For our study, we had as an input data an STL file and as an output a file with G-code instructions. For this analysis, we chose three slicing tools as follows:

- Slic3r has an open source slicing tool version and can support extensions such as STL, OBJ, and AMF. Besides that, they implemented a few options that are not available on other slicing tools;
- Cura is an open-source slicing tool developed by Ultimaker and is offering everything you need for slicing and printing. It is capable of recognizing 3D data in files with the extension STL, OBJ, DAE, and AMF. It is offering many default profiles for FFF 3D printing and a user-friendly interface;
- Simplify3D is an advanced slicing used in more than 120 countries, and it is compatible with most of the equipment that is using FFF technology for manufacturing products. It is capable of reading files as STL, OBJ, and 3mf. Some of the advantages are the slicing speeds, constant and stable updates, easy to remove sports, facts that are justifying the price of a license.

All manufactured probes used the same configuration for the printing parameters to ensure the reproducibility of execution and comparable results (Table 1).

Table 1

Printing Parameters

<table>
<tr><td rowspan="3">Printing speed</td><td colspan="2">Speed for nonprinting moves:</td><td>150 mm/s</td></tr>
<tr><td colspan="2">Speed for printing</td><td>45 mm/s</td></tr>
<tr><td colspan="2">First layer</td><td>20 mm/s</td></tr>
<tr><td rowspan="7">Internal and external geometry</td><td colspan="2">Infill</td><td>20%</td></tr>
<tr><td colspan="2">Infill pattern</td><td>rectilinear</td></tr>
<tr><td colspan="2">First layer height</td><td>0.2 mm</td></tr>
<tr><td colspan="2">Layer height</td><td>0.2 mm</td></tr>
<tr><td colspan="2">Number of bottom layers</td><td>4</td></tr>
<tr><td colspan="2">Number of top layers</td><td>4</td></tr>
<tr><td colspan="2">number of perimeters</td><td>3</td></tr>
<tr><td rowspan="4">Printing temperature</td><td rowspan="2">Nozzle temperature</td><td>First layer</td><td>215^{o}C</td></tr>
<tr><td>Other layers</td><td>210^{o}C</td></tr>
<tr><td rowspan="2">Bed temperature</td><td>First layer</td><td>60^{o}C</td></tr>
<tr><td>Other layers</td><td>50^{o}C</td></tr>
<tr><td rowspan="2">Advanced settings</td><td colspan="2">Extrusion multiplier</td><td>0.98</td></tr>
<tr><td colspan="2">Retraction distance</td><td>0.8 mm</td></tr>
</table>

4. Quality Factors

The main goal of the manufacturing process is to provide physical models respecting technical documentation and geometrical boundaries given by the 3D model. Below are described as a set of controllable factors that can influence the quality of 3D printed parts.

Poor retraction: During the 3D printing process, the extrusion head is switching between two operations: active extrusion combined with the necessary moves to define the boundary of the model and the travel movements from one region of the model to another. For this reason, the extrusion system must be capable of turning off the material flow through the nozzle until it is reaching the next printing location. If retraction performers too soon, gaps may occur, and it is too late, small drops can be observed (Simplify3D 2019). This defect is observed easily because between the two or more printing regions, spiderweb-like extra material may occur.

Adhesion degree: The adhesion degree of layers is the essential factor for the 3D printed parts, to ensure the proper quality of the product. The first layer must have a proper cohesion on the build plate. All the other layers built upon the first one needs “a strong base” to provide stability to the entire model. If the adhesion is not sufficient, warping may occur or even part detachment from the build plate. A skirt added of 5 mm width for increasing the area of contact for ensuring proper adhesion of the parts over the building plate for each piece.

5. Metrics

To be able to quantify and compare the differences between slicing software and their capacity to ensure a good quality print, a set of measurements must perform.

Deviation measurement: A standard method used in the industrial practice is to measure the dimensional deviations and compare them with the CAD data. In the 3D printing, we can presume two extremes scenarios that are related to the extrusion flow. If the quantity of material forced through the nozzle is low, under extrusion is occurring, and if the material flow is too high, over extrusion appears. The flow rate can be controlled using the 3D printing machine software, but cannot fully constrain because of the precision of filaments. Thus, in a single process, we can obtain sections with under extrusion and with over extrusion. To facilitate the measuring procedure of deviations, those were divided into categories measuring ranges, as can be seen in Table 2.

For this study, we made several assumptions regarding Fused Filament Fabrication. In the first place, we presume that the results for the manufacturing process would be the same for all models. This similarity refers to if we repeat the process on the same 3D printer, expects that if an error appears on one model, this event is the same for the other models as well. Regarding the nozzle, was used a single brass nozzle of 0.4 mm since the lifetime is sufficient for this study. All parts built-in individual processes had the same position on the build plate for ensuring the reproducibility of the manufacturing process.

Table 2
Measurement Criteria

Abbreviation	Name	Description
(R)	Removable	Surfaces not affected by removal
(D:0.2 mm)	Small deviation	Deviations more than 0.2 mm
(D:0.2-1 mm)	Medium deviations	Deviations among 0.2-1 mm
(D:1-2 mm)	Large variations	Deviations among 1-2 mm
(D: ≥2 mm)	Coarse deviations	Deviations bigger than 2 mm
(G:<1 mm)	Small gaps	Gaps smaller than 1 mm
(G:1-2 mm)	Medium gaps	Gaps among 1-2 mm
(G:2 -5 mm)	Large gaps	Gaps among 2-5 mm
(G: ≥5 mm)	Very large gaps	Gaps bigger than 5 mm
C	Catastrophic	The model has no similarities with 3D data

6. Evaluation of the Slicing Tools

In this section, we evaluate the chosen slicing tools using test models. Beams test was made using three different models and aim to evaluate the dimensional accuracy for simple geometries, the beams having the cross-sections circular, square, and hexagonal (Table 3).

Table 3
Values of Printing Time and Mass for Printed Models

Test plate		Slicing tool	Nozzle Size [mm]	Layer Height [mm]	Printing Time [h: min]	Mass [g]
Circular beams		Slic3r			02:06	24.62
		Cura			02:07	23.00
		Simplify 3D			02:05	22.68
Square beams		Slic3r			02:12	25.33
		Cura	0.4	0.2	02:11	24.00
		Simplify 3D			02:09	23.41
Hexagonal beams		Slic3r			02:10	24.85
		Cura			02:09	24.00
		Simplify 3D			02:07	22.93

Even if the circular shape does not present complexity, a small future size, less than 5 mm, may impose difficulties in respecting the dimensional accuracy of the desired model. The square shape can be considered the most "natural" shape that a 3-axis machine can execute. Even so, considering the FFF deposition way, small gaps can occur on the top surfaces, where the extrusion head tries to close the profile. The hexagonal shape can provide information regarding the capacity of the slicing tool to generate proper movements to ensure the dimensional accuracy of the for small features size under 5 mm WAF. Under this dimension, the profile tends to curve into a circular shape.

All features were measured three times. With those values, we determined the arithmetic mean (1) of the manufactured specimens. Furthermore, the standard deviation (2) was determinate to evaluate the variation of the resulted beams compared to the absolute values (see resulted values in Table 5). All used equations are below:

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{1}$$

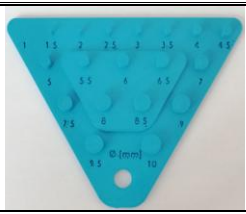
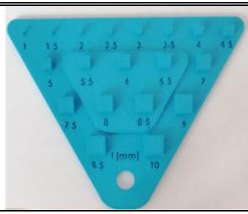
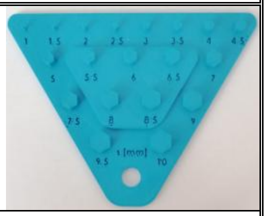
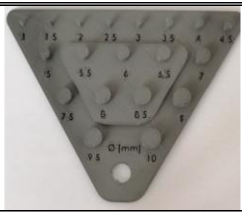
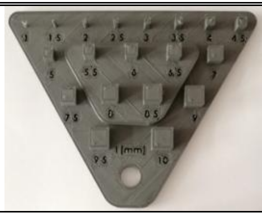
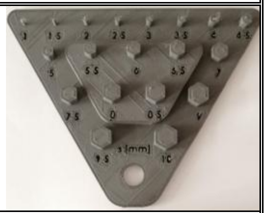
$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - x_0)^2} \tag{2}$$

As we can see, the printing time is similar for all slicing tools. The differences regarding printing time do not overreach three minutes – the same remark made, but for the mass variations. The mass differences are not exceeding more than 3 g. Those printing time variations are normal because each slicing tool has a unique algorithm to generate the path for the extrusion head.

Regarding the different values of the mass, the variation of the extrusion width can be a plausible explanation. The extrusion nozzle has a diameter of 0.4 mm, and every slicing tool is coming with the specific default extrusion width, established as being optimal (for example, Simplify3D is using 0.48 mm width and Slic3r are using 0.45 mm width). In the ratio printing time-used material, Simplify3D had the best results.

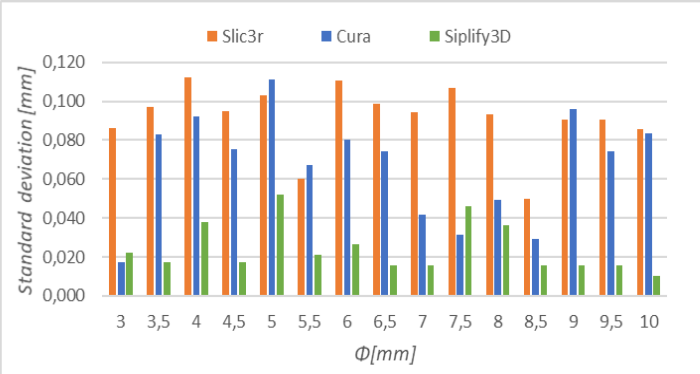
After the visual analysis of the resulting parts, several differences regarding surface quality of cylindrical beams had observed. All 3 models are presenting small gaps at the contours closing, especially at the numbers used for indicating features size. Small gaps also occurred on top of the beams, and the majority are associated with the parts created by Simplify3D. Regarding the adhesion of the first layer on the build plate, we can observe that all three parts presented footprints of under-extrusion on the broader side of the parts, and in the case of the Cura model, we can also observe regions with over extrusion.

Table 4
Print Results and Gaps Values for Each Slicing Tool

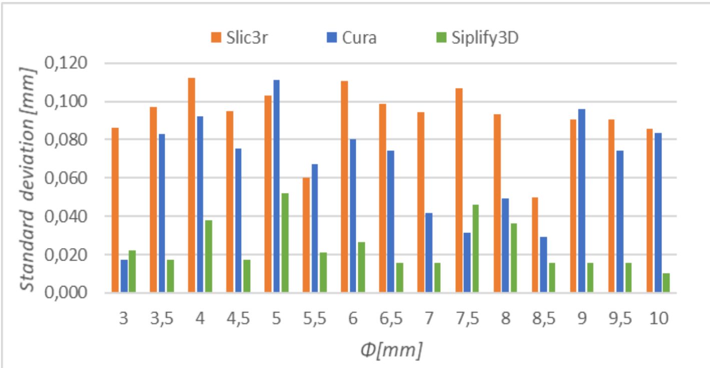
Beam test	Circular beams	Square beams	Hexagonal beams
	Printed part		
Slic3r			
Gaps	≤ 0.8 mm	≤ 0.84 mm	≤ 0.84 mm
Cura			
Gaps	≤1.15 mm	≤ 2.15 mm	≤ 3.19 mm
Simplify 3D			
Gaps	≤ 0.7 mm	≤ 0.97 mm	≤ 2.19 mm

In the case of square beams, by analyzing the bottom surfaces, we concluded that the previous remarks regarding the first layer adhesion are valid, with the mention that in the case of Slic3r over extrusion was also observed. Regarding the top surface texture, an overlap of the extruded regions appeared, the most outward being on the Cura models, followed by Simplify3D. The regions with gaps have appeared around the indicating numbers for all 3 parts. For the Cura model, those are visible on top surfaces of the beams, and insufficient retraction has occurred.

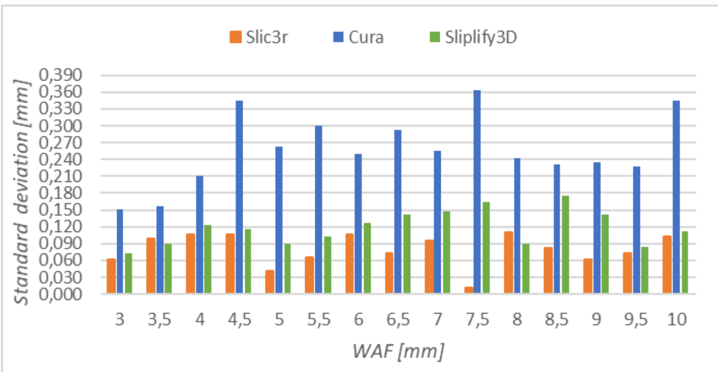
Through analysis of the hexagonal beams, again, adhesion issues observed, like in the case of the circular beams. Regarding the surface texture, once more, the best results were obtained using the Slic3r slicing tool, followed by Simplify3D and Cura. It is to mention that all regions with gaps mentioned before are alike. Relative to the insufficient retraction issue, the remarks made at the previous topic are similar in consistency and aspect.



a



b



c

Fig. 3 – Standard deviations graphs for all slicing tools:
a – Circular beams; *b* – Square beams; *c* – Hexagonal beams.

Table 5

Data Measurement and Processing

Slicing tools		Slic3r		Cura		Simplify3D	
Probe	Abs.	*Avg.* [mm]	*s* [mm]	*Avg.* [mm]	*s* [mm]	*Avg.* [mm]	*s* [mm]
Circular beams	3	2.930	0.086	2.993	0.017	3.007	0.022
	3.5	3.423	0.097	3.433	0.083	3.493	0.017
	4	3.917	0.112	3.940	0.092	4.023	0.038
	4.5	4.427	0.095	4.470	0.075	4.507	0.017
	5	4.917	0.103	5.087	0.111	5.040	0.052
	5.5	5.460	0.060	5.517	0.067	5.497	0.021
	6	5.913	0.110	5.950	0.080	5.993	0.026
	6.5	6.420	0.098	6.560	0.074	6.497	0.016
	7	6.923	0.095	7.030	0.042	7.003	0.016
	7.5	7.423	0.107	7.520	0.032	7.533	0.046
	8	7.927	0.093	8.037	0.049	8.000	0.036
	8.5	8.480	0.050	8.523	0.029	8.503	0.016
	9	8.927	0.091	9.077	0.096	9.003	0.016
	9.5	9.427	0.091	9.547	0.074	9.510	0.016
	10	9.933	0.085	10.060	0.084	10.007	0.010
Square beams	3	3.027	0.045	3.250	0.315	3.117	0.148
	3.5	3.523	0.038	3.680	0.222	3.617	0.154
	4	4.053	0.070	4.147	0.195	4.150	0.185
	4.5	4.553	0.066	4.733	0.296	4.660	0.196
	5	5.030	0.064	5.153	0.194	5.213	0.277
	5.5	5.537	0.076	5.717	0.266	5.643	0.176
	6	6.033	0.069	6.193	0.239	6.147	0.191
	6.5	6.583	0.114	6.730	0.283	6.693	0.277
	7	7.153	0.247	7.260	0.325	7.210	0.286
	7.5	7.590	0.131	7.750	0.307	7.697	0.246
	8	7.983	0.078	8.237	0.297	8.133	0.171
	8.5	8.537	0.045	8.680	0.221	8.627	0.158
	9	8.947	0.066	9.110	0.136	9.130	0.160
	9.5	9.450	0.071	9.700	0.251	9.590	0.117
	10	10.003	0.029	10.157	0.195	10.127	0.163

Table 5
Continuation

Slicing tools		Slic3r		Cura		Simplify3D	
Probe	Abs.	*Avg.* [mm]	*s* [mm]	*Avg.* [mm]	*s* [mm]	*Avg.* [mm]	*s* [mm]
Hexagonal beams	3	2.990	0.061	3.107	0.151	3.043	1.424
	3.5	3.450	0.099	3.603	0.157	3.567	1.869
	4	3.933	0.106	4.167	0.211	4.090	2.200
	4.5	4.423	0.106	4.780	0.344	4.590	1.961
	5	4.987	0.041	5.170	0.262	5.067	1.316
	5.5	5.463	0.065	5.707	0.301	5.583	1.493
	6	5.920	0.107	6.173	0.249	6.103	1.693
	6.5	6.453	0.073	6.713	0.292	6.613	1.714
	7	6.923	0.095	7.193	0.254	7.117	1.639
	7.5	7.503	0.012	7.747	0.364	7.623	1.618
	8	8.017	0.110	8.163	0.242	8.070	0.867
	8.5	8.490	0.083	8.680	0.231	8.640	1.620
	9	8.950	0.062	9.187	0.234	9.107	1.171
	9.5	9.480	0.073	9.680	0.227	9.567	0.697
	10	9.947	0.103	10.260	0.344	10.083	0.826

7. Conclusions

Considering the assumptions described previously regarding the reproducibility of the errors, those were confirmed because all manufactured models presented the same issues at a lower or higher degree. By analyzing the printing time, globally, the best resulted using the Simplify3D (see Fig. 3), and this remark is valid also for the used raw material quantity.

Regarding the first layer adhesion, globally, the best results were provided by the Simplify3D slicing tool, followed by Slic3r. In the case of the Cura software, was observed a split between regions with under-extrusion and over-extrusion. As was mentioned initially, the insufficient retraction drives to an excess of material deposited over the external surfaces of the features. If that does not represent an inconvenience for the medium feature sizes (over 5 mm), for smaller sizes can be harmful because of the high area of contact relative to the feature size.

Because of those, the parts created using Cura tool, presented a poor dimensional accuracy for the small features. The arithmetic mean for measured deviations did not surpass the value of 0.2 mm, affirmation valid for all three sectioning tools. Of course, there are some deviations from this pattern. For some features, the variation exceeded the value of 0.2 mm, but those were met locally.

Referring to the gap sizes, all manufactured models, there were observed three categories of gaps, small, medium, and large, according to Table 1, the most significant difference has a value of 3.19 mm (see Table 4). Gaps situated the regions without influence under the measurements, were appreciated for aesthetics considerations.

Overall the best precision was obtained through the Simplify3D followed by Slic3r and, in the end, Cura. Overall, the best accuracy occurred in the circular profiles, followed by square profiles and hexagonal ones.

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INFLUENȚA PROGRAMELOR DE SECȚIONARE ASUPRA PRECIZIEI DIMENSIONALE A MODELELOR IMPRIMATE 3D

(Rezumat)

În momentul de față, Fabricarea de Filament Fuzibil oferă multe posibilități în ceea ce privește fabricarea pieselor, pe baza informațiilor 3D. Pentru a obține modele calitative, este necesară o configurație riguroasă a programelor de secționare, iar aceasta poate diferi în funcție de echipamentul și materia primă folosită. Rolul unui program de secționare este de a converti informația 3D într-un set de instrucțiuni pe care imprimanta 3D îl poate citi și rula. În mod implicit, programele de secționare dispun de varii opțiuni în ceea ce privește generarea instrucțiunilor G-code și, prin aceasta, influențează direct calitatea și precizia dimensională a pieselor rezultate. Având în vedere multitudinea de variabile care pot influența acest proces și efectul acestora asupra calității pieselor rezultate, obiectivul principal al acestui studiu a fost acela de a studia influența programelor de secționare, asupra preciziei dimensionale a modelelor fabricate aditiv. S-a constatat că fiecare program de secționare prezintă particularități în generarea instrucțiunilor G-code, rezultând astfel probe cu niveluri diferite de precizie.