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Influence of Control Parameters on Consumer FDM 3D Printing

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Abstracts: Rapid prototyping (RP) is a set of technologies that permits building a physical model directly from its design by implementing a single automatic process using a 3D model of the object to be printed. RP systems can be based on different Additive Manufacturing (AM) technologies, such as a Fused Deposition Modeling (FDM) machine that works by extruding and melting together fused plastic filaments, drawing the boundaries and filling the model thin layer by thin layer. Low-cost FDM 3d printers do not work well automatically but require of a calibration phase because the best configuration settings in the slicing software are unknown, and the number of parameters values that needs to be manually defined is very large. The scientific literature reports many interesting articles on this topic, describing how the process can be improved by choosing the correct values of various parameters. Internet websites such RepRap.org discuss 3D printers and ppost detailed FAQ sections where users described improvements in 3D printing with simple methods but with great effort in terms of costs and time. Yet not all questions are answered. This paper would introduces: a) a new method for the analysis of the slicing software parameters that can be done with easy models; b) a second method for improving the effects of the parameters that shows a higher influence in the signal-to-noise ratio analysis.

Keywords. NIST Artifact, FDM, Rapid Prototyping, RepRap, Digital Fabrication

Introduction

Rapid prototyping (RP) is a set of technologies that permits building a physical model directly from its design using a single automatic process based on a 3D model of the object to be printed. RP systems can be based on different Additive Manufacturing (AM) technologies, such as a Fused Deposition Modeling (FDM) machine that works by extruding and melting together fused plastic filaments, drawing the boundaries and filling the model thin layer by thin layer. Each layer deposition process follows a precise path, usually programmed by a software that orients and slices the 3D model, allowing for choices of deposition parameters. Low-cost FDM 3D printers do not work well automatically; they require of a calibration phase because the best configuration of settings in the slicing software is unknown, and the number of parameters values that must be manually defined is very large.

Scientific literature reports many interesting articles that describe how the process can be improved by choosing the correct values of some parameters. In a study published by Johnson [1], an open source AM system was evaluated in terms of geometric accuracy using a benchmarking model designed ex novo, printed varying

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values of the Slicing software parameters. Other benchmarking models can be found in [2] [3] [4] [5] designed and printed varying some slicing parameters such as layer thickness, raster width and nozzle speed using an AM open-source printer. In [6] authors analyzed different benchmarking model designs and described his methodology for choosing the printing features that evaluate errors committed by RP machines FDM and Stereolithography (SLA). Other papers deals with printing parameters to identify the critical ones for dimensional accuracy [7] [8] or surface finish [9] [10]. More general consideration can be found on different precision of RP systems and processes [11] [12] and about testing procedures [13].

The internet has websites such as RepRap.org [14] discussing 3D printers. These sites contain detailed FAQ sections in which users describe improvements in 3D printing with simple methods but with a great effort in terms of costs and time, yet not all questions are answered. This paper introduces a new method for the analysis of the slicing software parameters that can be done with easy models and a second method for improving the effects of the parameters that show a higher influence in the signal-to-noise ratio analysis.

1. FDM Process

The FDM printer works by melting a slim filament of thermoplastic material using settings that include section dimension, flow and temperature. The distance between the nozzle and bed (not a parameter of the filament) also influences the whole process and requires a calibration phase. Those properties derive from control parameters of the printer that are set by the slicing software.

Slicing softwares require a certain number of parameters, depending on the FDM printer to be used and the user-friendly approach of the software. Depending on the software, a standard configuration can contain a large number of parameters that are implicitly defined, but it is not easy to understand where, what and how to modify those values. Learning the best configuration is the first obstacle that everyone must overcome before starting a 3D printing job.

Settings contained in the slicing software influence the whole process because they control the characteristics of every drop of extruded fused plastic. Once these parameters are set, we can produce an extruded filament characterized by a magnitude expressed in terms of *Layer Height* and *Extrusion Width* (Figure 1). Raising the temperature influences the extrusion process because the viscosity alters as the nozzle reaches the melting point, so filament dimensions can change during printing.

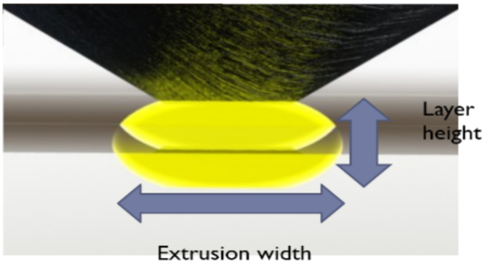

Figure 1. *Extrusion Width* and *Layer Height* are measured on a drop of melted plastic extruded by the heated nozzle.

The correct choice of parameter values can produce improvements in the quality of prints in terms of dimension errors. In this study, we will consider four parameters (Table 1) related to *Extrusion Width*, described below as control factors, and other parameters described as standard fixed values. Figures 2-4 show *Perimeters Extrusion Width, Infill Extrusion Width, Solid Infill Extrusion Width and Top Solid Infill Extrusion Width*.

Table 1. Default settings

Parameter	Setting
Extrusion Width	Variable
Infill Extrusion Width	Variable
Solid Infill Extrusion Width	Variable
Top Solid Infill Extrusion Width	Variable
Extrusion temperature	210 [˚C]
Bed Temperature	65 [˚C]
Layer Height	0.25 [mm]
Max Speed	25 [mm/s]

The other parameters are used by slicing softwares to obtain the required filament width and they do not affect directly the precision of printed objects, as suggested in [15].

The slicer software, as configured, produces a *machine code* that can be executed by the 3D printer. Each row of this code contains words, that are a combination of numbers and letters. These combinations produce displacements, raise the temperature of the components, and pull the filament flow through the hot-end of the extruder in the 3D printer. The most commonly used software are Cura [16], Slic3r [17] and Simplify3d [18], each utilizing a different number of settings.

Actually, there are two methods for looking for the *slicer configuration*: a systematic approach and the practical one. The first approach is a scientific method that uses a complex benchmarking model for obtaining a degree of performance, varying the slicer configuration many times, resulting in the best values but spending too much time and material in printing scraps. Evaluation of the best configuration can be obtained after a measurements phase of all the features printed on each sample, as described in [1]. The second approach requires printing objects that contain strange shapes with a few features that easily can show the improvements. This approach does not consider a phase of measurements and does not use a statistical model for understanding the parameters behavior when the best choice is made.

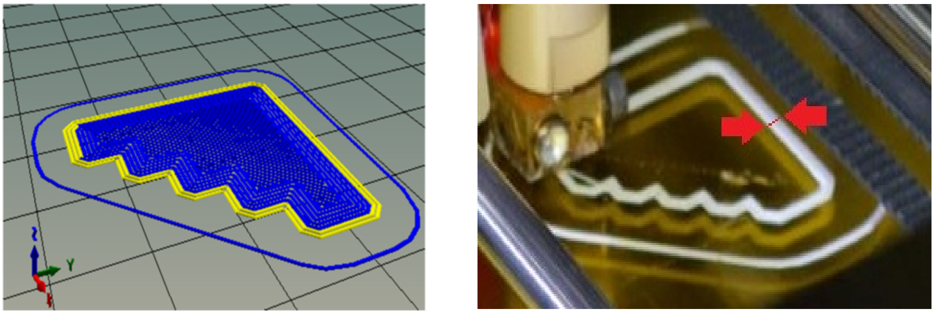

Figure 2. *Perimeters Extrusion Width* measured in the slicer (left) and after the extrusion (right).

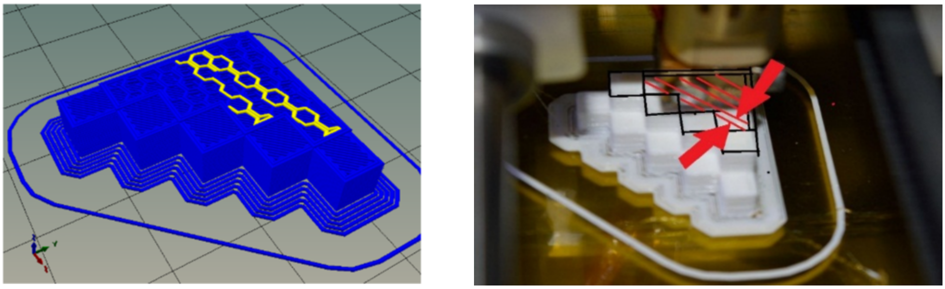

Figure 3. *Infill Extrusion Width* measured in the slicer (left) and after the extruion (right).

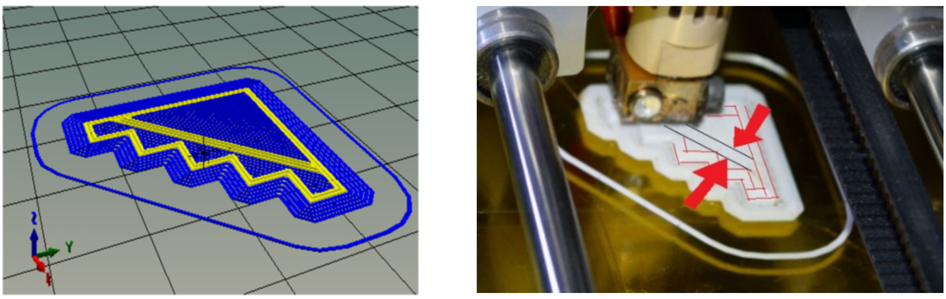

Figure 4. *Solid Infill Extrusion Width* in the slicer (left) and after the extrusion (right).

2. The design of experiments

Table 2. Control Factors Values (mm)

Parameter	Factor	Level 1	Level 2	Level 3
Extrusion Width	1	0.2	0.4	0.6
Infill Extrusion Width	2	0.2	0.4	0.6
Solid Infill Extrusion Width	3	0.2	0.4	0.6
Top Solid Infill Extrusion Width	4	0.2	0.4	0.6

Printed parts easily became scraps after a bad slicer setup. Because of the high number of control parameters, it is very difficult to foresee the effects on printed parts after combined changes in the slicing software. A Design of Experiments was planned (Figure 5), using a simple model, to investigate the influence [19] that each control factor has on the precision of printing and to allow the identification of the main factors influencing quality. A small number of these parameters were considered control factors because they can control the characteristics of plastic pushed through the nozzle. Other settings are chosen considering the default values available for the PLA filament.

The Taguchi method allows for a reduction of the number of experiments to a small number considering all the possible combination of parameters. For this research, we designed a *factorial partial experiment* following Taguchi's L_9 orthogonal array that combines different values of the same parameters investigated on three levels. The slicing software used for this study phase was Slic3r. Table 2 defines the control factors investigated and the values attached to each level, where the Level 2 is the standard value proposed for FDM printing activities. For these experiments, the parameters in the slicing software were varied on three levels. Table 3 defines the experiments required by a Taguchi method that should be evaluated to obtain all the combination of parameters for the smallest amount of experiments.

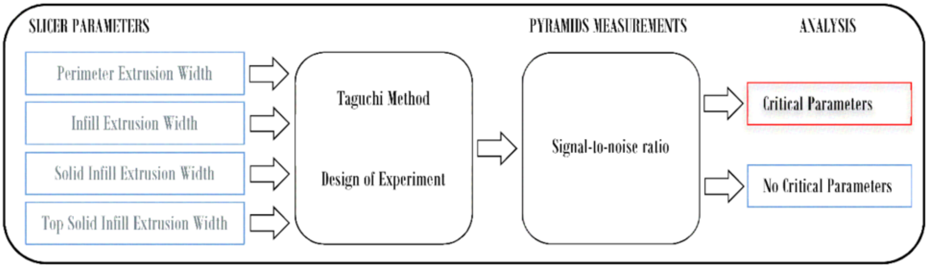

Figure 5. Flow diagram describing the whole process of data setting.

Table 3. Experimental cases based on Taguchi method L9(3^4)

Sample	Factor 1	Factor 2	Factor 3	Factor 4
1	0.2	0.2	0.2	0.2
2	0.2	0.4	0.4	0.4
3	0.2	0.6	0.6	0.6
4	0.4	0.2	0.4	0.6
5	0.4	0.4	0.6	0.2
6	0.6	0.2	0.6	0.4
7	0.6	0.4	0.2	0.6
8	0.6	0.4	0.2	0.6
9	0.6	0.6	0.4	0.2

Item number 56003 (Figure 6) from *thingiverse.com* [20] was choosen as a model because it is easy to print, fast to measure and has a large number of useful measurable features. Moreover, this model is commonly used in the necessary calibration phase (5 mm Calibration Cube Steps Pyramid) to improvie printing for most users. The model is a small, manageable pyramidal-shaped object containing five levels of cubes where the distances between each pair of parallel faces can be easily measured by a caliper, and it is simple to switch from a pair to another one.

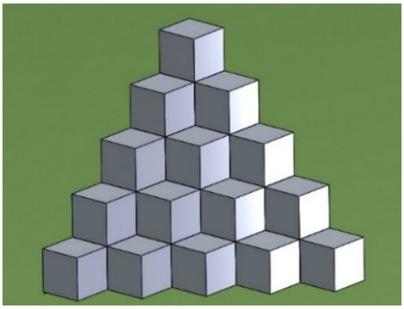

Figure 6. Pyramidal model

Compared to the benchmarking model, this model is open source and free downloadable, it has more measurable features on all axis because it is symmetrically shaped, uses a small quantity of matter for each printed sample and it prints quickly.

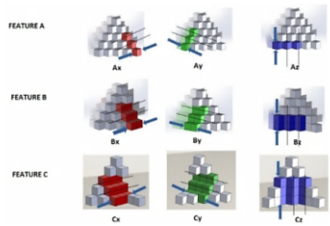

Figure 7. The number of adjacent cubes measurable more times in the same direction

Table 4. Summary of data

Parameters investigated (in the slicer)	4
Levels for each parameter	3
Total experiments	9
Samples per experiment	3
Measurements for each sample	27
Total features measured	729

The distance between the opposite faces of one cube are considered *Feature A*, the distance between the opposite faces of two consecutive cubes are considered *Feature B* and the distance between the opposite faces of three consecutive cubes are considered *Feature C* (Figure 7).

Each model was printed in three samples and each pyramid measured many times (Table 4), following a specific procedure: for each Feature, three measures were taken in three different positions for each x, y and z axes direction (arrows and black lines in Figure 7). These measurements were statistically compared with the corresponding ones in the virtual model.

3. Results of DOE

All data have been collected and evaluated (Table 5). Figure 8 shows the influence of the percentage of measurement errors related to each kind of Feature. In Figure 9, we observe the influence of these values on the percentage of error measured on the x, y, and z axes.

To evaluate the influence of these parameters on the precision of printed parts, we calculated the Signal-to-Noise Ratio. Table 6 show that the parameter with the highest Signal-to-Noise ratio value is *Perimeter Extrusion Width.*

Although it is clear that *Perimeter Extrusion Width* is a settable parameter at Level 2 for obtaining the max improvements in this kind of model, it is not clear if this

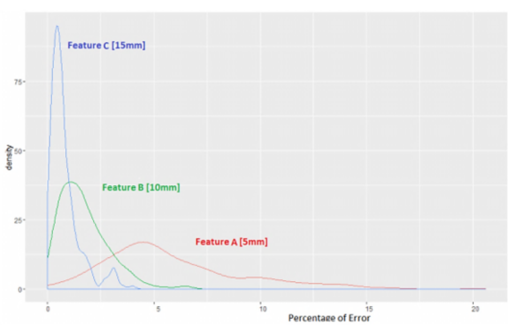

Figure 8. Density of frequency plot for the percentage of error in the measurements for three different features in the pyramidal samples.

Table 5. Summary of data of percentage of error in the measurements.

	Mean Value	**Standard Deviation**
Feature A	5.823	3.269
Feature B	1.704	1.154
Feature C	0.795	0.721
Feature X	2.620	3.009
Feature Y	3.266	3.387
Feature Z	3.778	2.537

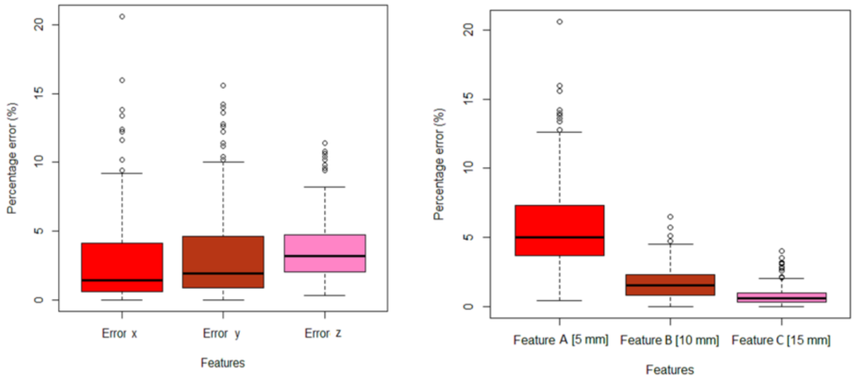

Figure 9. Percentage of errors in measurements respect for the different axes (left) and in respect to the magnitude of the distances in the features (right).

improvement can be obtained in other features or if more levels could help reduce the percentage of errors in the measurements. The *Perimeter Extrusion Width* also influences the error on the z-axis more than the x-y axes, and this behavior could be very different (Table 7).

Table 6. Signal-To-Noise Ratio results

Meaning	Level1	Level 2	Level 3
Perimeter Extrusion Width	0.322	1.227	0.282
Infill Extrusio Width	0.802	0.713	0.333
Solid Infill Extrusion Width	0.546	0.827	0.142
Top Solid Infill Extrusion Width	0.421	-0.106	0.874

Table 7. Signal-To-Noise Ratio results for z and x-y directions

Meaning	Level1	Level 2	Level 3
Perimeter Extrusion Width X-Y	0.538	0.319	0.026
Infill Extrusio Width X-Y	0.259	0.680	-1.090
Solid Infill Extrusion Width X-Y	1.331	0.190	-0.735
Top Solid Infill Extr. Width X-Y	0.375	-0.567	0.591
Perimeter Extrusion Width Z	0.528	3.108	1.593
Infill Extrusio Width Z	1.332	1.533	2.518
Solid Infill Extrusion Width Z	0.594	2.322	1.808
Top Solid Infill Extrusion Width Z	1.619	1.620	2.044

The parameters *Infill Extrusion Width, Solid Infill Extrusion Width* and *Top Solid Infill Extrusion Width* describe behaviors very different for the three levels of the parameter. The parameter *Infill Extrusion Width* remains smooth when the level changes and when the measures are taken in respect to the z axis; the spread raises when the measurements are taken along the x or the y axes. *Solid Infill Extrusion* exhibits the same behavior as *Perimeter Extrusion Width* but with a higher spread from the first level to last since the curve of the Signal-To-Noise Ratio on the z axis before raising and then decreasing shows a negative trend.

The parameter *Top Solid Infill Extrusion Width* exhibits the same behavior for the x-y measurements and for z measurements, but the magnitude of the central value (Level 2) is quite different, higher for the measurements along the z axis.

Based on control factors impact on slicer (Figure 10), *Perimeter Extrusion Width* influences a higher percentage of error when compared to the other factors (Figure 11) and is thereby defined as a *critical parameter*. To obtain more accuracy in the prints, we started a new optimization phase, analyzing a model with a large number of features and a higher number of levels of this critical parameter. This complex benchmarking model can be now used because of a reduced number of parameters to be analyzed. This variable is the only parameter appearing in every layer. Thus, it has more influence on the smoothness of the error curves and can improve the Signal to Noise Ratio more than can other parameters. It is possible that the other three parameters are unused or have values highly dependents on geometry.

4. Benchmarking Model

A detailed analysis was performed on a second benchmarking model, wich contain more features with a more complex shape, by varying the parameter *Perimeter Extrusion Width* in the same range of the previous benchmarking model but with more intermediate values. These features require more articulated movements of the extrusion head that can produce multiple effects on printing precision and create poor results in the quality of printed parts. Figure 11 shows this new benchmarking model, selected from those available in previous studies and published since the rapid prototyping process was created [6]. This is the NIST model.

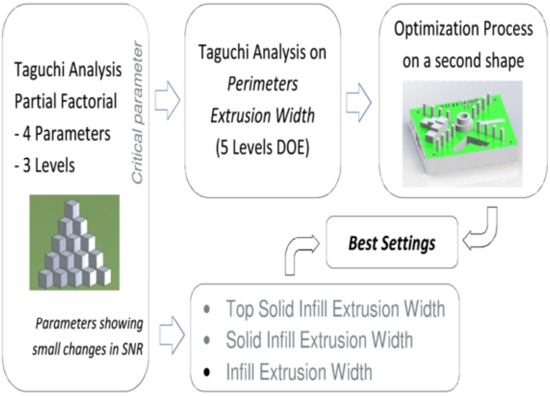

Figure 10. Flow diagram outlines the steps required in the process of optimization for slicer parameters.

The NIST model is a parallelepiped-shaped object with geometric features as circular holes, circular bosses, square holes and prismatic shapes on the superior and lateral faces.

Figures from Figure 11 to Figure 18 detail all considered features, all dimensions to be measured and in which positions measures must repeated. Table 8 lists nominal values for each of these dimensions and Table 9 lists measures multiplicity. The NIST artifact [21] permit measurement of many features and it is available an inspection worksheet edited for this purpose.

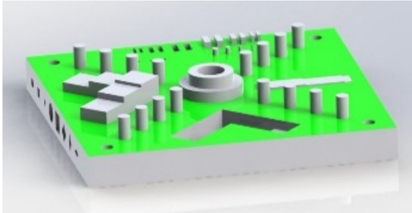

Figure 11. Square plate.

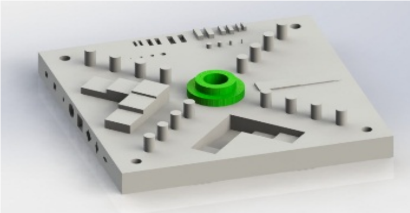

Figure 12. Bores and staircase.

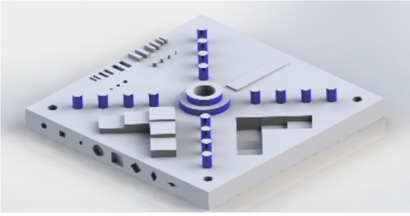

Figure 13. Angular Position of bosses and holes.

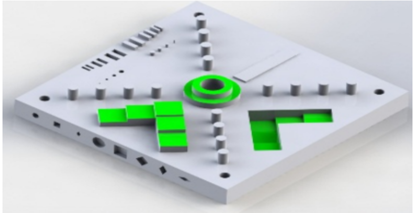

Figure 14. Staircase.

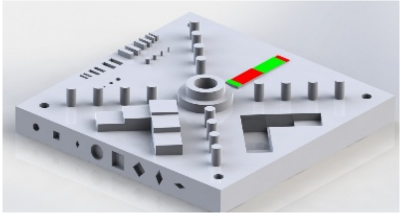

Figure 15. Ramps.

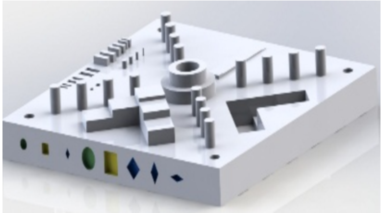

Figure 16. Lateral features.

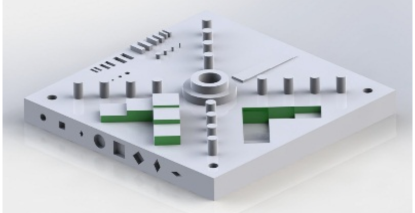

Figure 17. Lateral staircase.

Figure 18. Cylindrical features.

Table 8. Ideal feature dimensions(mm).

Features:	Description	Values [mm]
Square plate	Thickness	10
	Length x	100
	Length y	100

Central Hole	Inner Diameter	9.0
	Outer Diameter	14.5
	Bottom Diameter	20.5
Cylinders	Diameters	4
Staircases at the top of square plate	Outer Staircases	+3 | +4 | +5 | +6 | +7
	Inner Staircases	-3 | -4 | -5 | -6 | -7
Ramps	Step 1	+0.25
	Step 2	+0.50
Lateral Features		
Round Hole	Diameter	3
Square Hole	Side	3
Rhombus Hole	Diagonals	3
Round Hole (2)	Diameter	6
Square Hole (2)	Side	6
Rhombus Hole (2)	Diagonals	6
Rhombus Hole (3)	Main Diagonal	3
Rhombus Hole (4)	Main Diagonal	6
Lateral side of staircases	Width for one step	10
	Length for two steps	20
	Length for three steps	30
Cylindrical Bosses	Height	7
	Diameter	4

Table 9. Number of data acquired for each feature.

Features (test1)	**description**	**N data**
Square plate (1)	z-thickness	9
Square plate (2)	x-y sizes	4
Central hole	diameters	6
Angular holes	diameters	8
Staircase (1)	z-thickness	9
Staircase (2)	x-y width	30
Ramps	z-thickness	2
Lateral features	diameters, diagonal	27
Cylindrical features (1)	diameters	32
Cylindrical features (2)	z-thickness	11
Cylindrical features (3)	x-y cylinder spacing	12
Top plate features	z-thickness	6
Spacing angular holes	x-y sizes	2

5. Results of the experiments

The benchmarking model was printed for five different *Perimeters Extrusion Width*; all described features were measured and all measures were explored to obtain the Signal-To-Noise Ratios. Even if the peak of the curve in Figure 20 is at Level 3, the trend of the curve suggests that the choice of an intermediate value between levels 3 and 4 can improve results respect to the pyramidal model study.

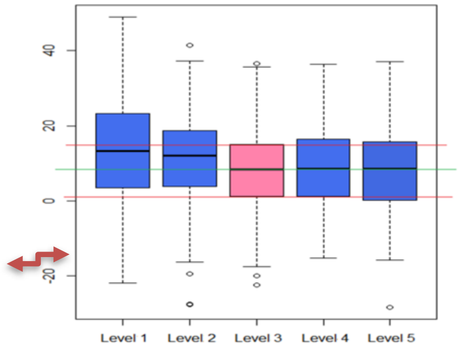

Figure 19. Boxplot diagram describing the percentage of error varying five levels in the parameter *Perimeters Extrusion Width*.

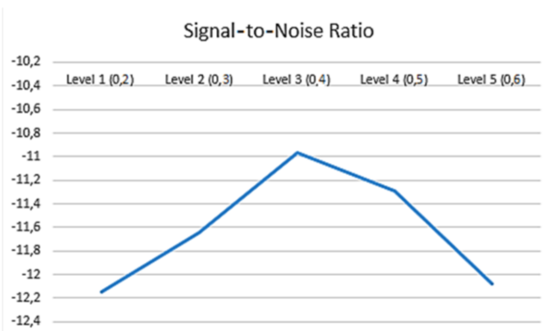

Figure 20. Signal-To_Noise Ratio diagram describing the effects of the modifications in respect to errors measured for each level of the parameter *Perimeters Extrusion Width*.

The results of the second experiment are represented in Figure 20, and they show that for a wide range of values, the parameter *Perimeters Extrusion Width* exhibits non-linear behavior, and the effects in terms of Signal-To-Noise Ratio can be read with more detail than in the previous analysis (Table 10).

Furthermore, this new analysis demonstrates that the parameter investigated with a different method exhibits the same behavior respect to the pyramidal method after evaluating the error in the measurements. The method can improve the printing, and it shows how the control factors work. When the control factors are more efficient, we obtain better performance of the whole process. For the kind of parameter investigated we obtained a good analysis that can be easily replicated to verify the chosen method.

Table 10. Results Summary.

Level	1	2	3	4	5
Perimeter Extr. Width	0.2	0.3	0.4	0.5	0.6
Mean Value	11.408	10.303	9.553	8.658	8.636
Standard Deviation	13.672	12.260	10.922	10.800	11.804

The best value of the parameter *Perimeter Extrusion Width* may be contained in [0.4-0.5]. Figure 19 shows that the 50th percentile improve values higher than 0.4; the third percentile raise its magnitude for the value 0.5 of *Perimeter Extrusion Width*, with the whole distribution smaller for the 0.5 case.

6. Conclusions

The series of experiments show that the parameters selected in this analysis can be considered control factors and can influence the quality of the FDM manufacturing process. In the previous paragraphs we demonstrated that the *Extrusion Width* contains other kinds of hidden parameters, and they can be changed to reduce the percentage of error. In the authors' experience of 3D printing of more then 100 parts, the time-saving in the overall "design for additive manufacturing" process is about 40% with a reduction of scraps of about 60%. The contributions that we have reached in this study are: the definition of a new method that can be used for obtaining numerical results, and the analysis and comparison with the NIST artifact demonstrate that it works; the definition of a method that can easily be applied to many kinds of Rapid Prototyping Machines because it uses a very simple technique for understanding the errors along three axes; the reduction of the time spent for tests by opportunely setting the parameters that have been investigated in this paper; the demonstration that the parameter *Extrusion Width* hides other parameters inside that can influence the shape of the object; the demonstration that the parameter *Perimeter Extrusion Width* can improve the effects on the printing process, thereby reducing the number of errors.

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