Optimizing Fabrication Outcome in Low-Cost FDM Machines. Part 2 - Tests

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Several models of FDM machines, characterized by different architecture and hardware components, have flooded the market in the last 5 years. As a result, given the high sensitivity of FDM to the specific machine characteristics, the search for optimal printing parameters is a renown problem. This two-parts paper proposes an easy-to-follow and low-cost procedure for the characterization of any given FDM machine. The method allows the evaluation of the effects of a wide selection of FDM process parameters on the quality of 3D printed parts. The first part focused on the definition of a series of metrics to be measured on a series of test prints to evaluate the quality of the produced parts. The evaluation of seven quality parameters on a single print is made possible thanks to: i) a specifically designed specimen that is made available to the user and ii) a rigorous and repeatable measurement procedure, which are both discussed in the first part of the paper. This second part presents the characterization procedure, the statistical tools used in the experimentation (DOE tools and principles are adopted throughout the experimentation) and provides guidelines to be used for the characterization of any FDM machine. The whole procedure is tested on a desktop FDM machine to demonstrate obtainable results, proving the efficacy of the proposed methodology and highlight strengths and drawbacks of the approach.

Keywords: Additive Manufacturing (AM), Fused Deposition Modeling (FDM), Process Optimization, Design of Experiments (DOE), 3D Printing.

1 Introduction

This paper is the second part of a study that aims at devising an effective and practical procedure to allow the evaluation of the effects of multiple FDM process parameters on the performances of any machine. Indeed, a great variety of FDM machines, characterized by different performances and features, are available on the market. Industrial FDM systems, produced by most renown manufacturers, namely Stratasys, offer software solutions that are optimized for the architecture and charateristics of their machines. Less refined machines, on the other hand, typically exploit generic 3D printing software packages (e.g. Ultimaker Cura, Slic3r [1,2]) to generate the machine path and control the whole FDM process parameters. These software packages provide the user access to a large pool of settings and options to set up printing operations; sadly, lots of tweaking and fine-tuning is usually required in order to obtain a fully satisfying output.

The wide number of parameters and the great variety of machine hardwares introduce significant uncertainties in the definition of the optimal printing parameters, which depend also on the specific shape of the object to be manufactured. As a result, the search for the optimal set of parameters is typically carried out, by low-end FDM user, by means of a trial and error approach. This paper proposes a strategy that allows for a custom optimization of the entire FDM process, tailored on the specific features and performances of any FDM machine. The procedure has been devised to be easy to follow and it can be applied without the need of advanced equipment or measuring tools, by non-experts. Moreover, the proposed approach requires limited time and material resources.

In the first part of the paper, starting from a detailed description of existing procedures for the evaluation of the effects caused by different FDM process parameters, a novel approach to the problem is proposed. The discussed methodology distinguishes itself under two fundamental aspects: i) it allows the evaluation of the effects of a wide number of parameters (up to fourteen); ii) it is accessible and implementable by any FDM user. The first part of the article starts with the description of seven different metrics used to describe different quality aspects observable on the printed parts. Every metric can be evaluated by means of an effective, reliable and easy-to-follow procedure that is presented in detail. The procedure is supported by the development of a specific specimen (described in the first part of the paper) to be used in a series of test prints and by a set of detailed guidelines that the user needs to follow.

In this second part of the paper, the whole characterization procedure will be presented and discussed. In order to evaluate the effects of a wide number of process parameters, a coarse-to-fine analyisis, making use of two fractional two-level designs, is proposed to carry out the experimentation. The devised methodology is based on DOE principles and makes use of basic statistical tools. The entire procedure is presented with reference to the "S2" desktop FDM printer produced by Gimax 3D with propaedeutic purposes.

The framework discussed in this paper is depicted in Fig.1; the process starts with the selection of the parameters to be considered in the characterization procedure among all the FDM process parameters. Section 2 describes the strategy proposed for the selection of the parameters to be considered for the characterization of the printer. An initial set of 14 parameters that have been selected considering the settings that are typically most relevant and by analyzing similar studies in the literature, is proposed as possible starting point. This initial set is editable by the user according to their needs. Subsequently, two fractional two-level designs are required to perform a coarse-to-fine analysis of the process. The first fractional plan, described in Section 3, provides a first rough characterization of the process; only first-order effects, identifiable with a low-resolution plan, are identified and isolated by the analysis. Accordingly, a second fractional design (Section 4) considers five factors, that are selected as the most influent in the first part of the experimentation; by selecting a limited number of parameters is possible to achieve a high resolution in the final results. The whole procedure requires a total of 96 test prints, that is if every run is repeated three times in order to increase the statistical validity of the results. The article describes the setting of the experiments, the strategy used to select the parameters to be part of the second fractional design. All the steps are discussed using a low-end FDM machine as example; the results obtained applying the method in the case study are presented to demonstrate a possible interpretation of the measured data. Finally, strengths and drawbacks of the presented method are discussed in the Conclusions Section.

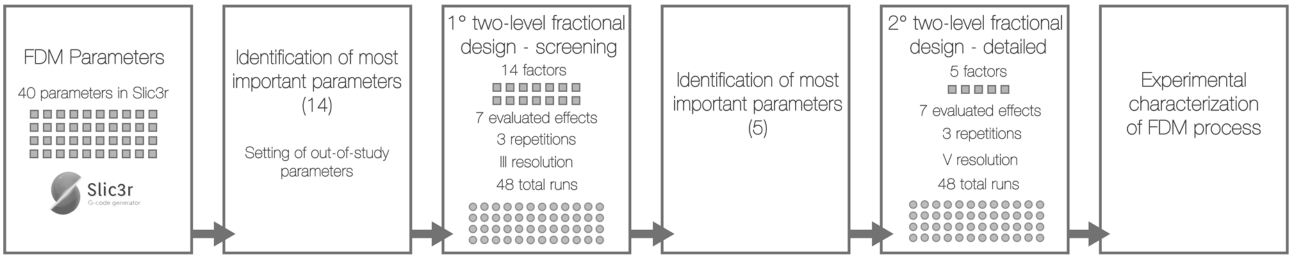


Fig. 1 *Recommended FDM characterization procedure*

2 Selection of process parameters known to have relevant effect on the quality of the 3D printed

As mentioned in the introductory section, typical 3D printers implementing the FDM process allows to set a number of parameters once properly managed by a given software package. In particular, up to 40 process parameters (and options) can be set, each one of them influencing the quality of the 3D print. As already mentioned, in the present work the open source Slic3r 1.2.9 software [2], offering access to a vast set of parameters and enabling the user to completely control the process, is used to manage the slicing process an FDM printer.

The first step of the proposed procedure, is to reduce the number of print parameters to a reasonable number for carrying out a factorial design (i.e. 14 parameters). Actually, a complete study taking into consideration all the available parameters is impracticable since it imposes an enormous number of runs. Accordingly, the selection of the 14 factors was performed taking into consideration literature results indicating most influent parameters, information provided by the Slic3r guide, and the authors' experience in the field. Both traditionally important parameters and interesting secondary settings were taken into consideration, in order to fulfill this work goals. The list of 14 factors considered in the preliminary experimentation plan is hereby reported together with a motivation for their choice.

- **Layer height [mm]** – is the layer thickness, one of the "main" FDM parameters [3], as it directly determines the vertical resolution of the print; a higher value grants faster prints at the cost of a lower quality.
- **Perimeters** – a natural number defining how many external perimeters are created for each layer. A higher number of perimeters generally guarantee a higher solidity of the part [4], but impose a higher build time.
- **Solid Layers** – a natural number defining the number of top and bottom layers (i.e. constituting the "shell" of the print) that are built with a 100% infill.
- **Fill Density [%]** – a percentage value indicating the density of the infill used to print the central parts of the model.
- **Fill Pattern** – the geometry of the pattern used to build the internal part of the model. In this study two of the most common and different patterns (i.e. honeycomb and rectilinear) were considered.
- **Top Solid Infill** [%] – a parameter controlling the extrusion width of the top external layers; a thinner extrusion could theoretically improve the surface finish; the parameter is expressed as percentage value with respect to the standard width.
- **Perimeters speed, small perimeters speed, external perimeters speed, infill speed [mm/s]** - print speed parameters, controlling the printing speed for each part of the model.
- **Extrusion Multiplier [%]** – percentage value controlling the amount of material that flows through the nozzle with respect to the standard amount evaluated by the software; is sometimes adjusted according to the machine characteristic; a higher material flow can improve the solidity of the print, a lower flow can guarantee cleaner

external surface and sharper angles, allowing for better details.

- **Extruder temperature [°C]** – temperature of extrusion; higher temperatures improve the material fluidity, lower temperatures generally produce overhang surfaces of higher quality.
- **Retraction** – a Boolean parameter: if set to 1 activates the retraction of the filament between the extrusions, to prevent oozing.
- **Quality** – a Boolean parameter, describing the activation of a set of refined decision-making logics that are responsible for: i) the generation of extra perimeters to avoid gaps, ii) the generation of extruder paths that do not intersect with external perimeters; iii) detection of thin walls that can be reduced into a single-wall structure and iv) apply bridging options (fans on and slow printing speed) even to overhang surfaces.

It is important to note that some choices, regarding the parameter selection, had to be made at the start of the study of the procedure describe in the present article. Specifically, the specimen has been designed considering a nozzle diameter of 0.4 mm (the most commonly used [5]) and its geometric features have been tuned in dimensions according to this choice. Similar choices have been made at the start of the study for the material used for the prints and other settings, which are reported in Tab. 1; the setting of such parameters has been done referring to a standard configuration for the FDM process, trying to avoid values that could trigger undesired effects.

Tab. 1 *Parameters and settings left untouched during the study. Parameters names refer to Slic3r.*

Parameter / Setting Name	Value used for validating the procedure
Extruder diameter	0.4 mm
Material Used and filament diameter	PLA - 1.75 mm – produced by Eumakers
Bed Heating	(Disabled)
First layer height (Layers)	100%
Combine infill every n° layers	1
Only infill where needed (Boolean Value)	0 (not active)
Solid infill every n° layers	0
Fill angle	45°
Solid infill threshold area	70 mm² (default)
Only retract when crossing perimeters (Boolean Value)	0 (not active)
Default extrusion width	0 (default)
First layer	200%
Infill & solid infill	0 (default)
Solid infill speed	100% (relative to infill speed)
Top solid infill speed	20 mm/s
Bridges speed	50 mm/s
Gap fill speed	20 mm/s
Travel speed	120 mm/s
First layer speed	75%
Skirt Settings	• loops:4 • distance from object: 6mm • skirt height: 1

3 Implementation of a preliminary two-level fractional factorial design

The characterization procedure has been applied by the authors in the characterization of a desktop FDM printer to highlight its strengths and amend possible weaknesses. The detailed implementation of the steps previously described is discussed in the following text with reference to this specific case study for sake of clarity. The experimented printer consists of a Gimax 3D FDM printer "S2" (Fig. 2) with a 400 mm cubic build volume and equipped with a heated bed and two extruders. It is worth noting that the same analysis could be performed on other models of FDM printers.

The setting of the experimentation plans described in the following text has been carried out using Minitab [6], a statistics software package that offers semi-automatic tools to build, populate, and manage two-level fractional designs of experiments. Moreover, as it is discussed in the text to follow, Minitab provides automatic tools to extract the desired results in form of graphs and charts reporting the influence of the parameters considered in the analyises. Similar free software packages to perform statistical analysis, to be used by future users of the procedure, can be easily found online; alternatively, depending on the user' preferences, the same principles and statistical tools could be reproduced in an Excel spreadsheet.

For the selection of the two levels considered for the factors included in the experimentation typical ranges of functioning for each parameter are considered. The two levels are set near the limit of the suggested parameter range to cover the entire functioning range and every possible effect, as depicted in Tab. 2.

***Tab. 2** Factors included in the study and values set for the 2 levels.*

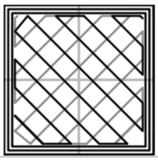
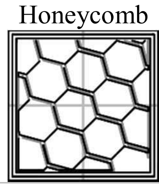
N°	Factor	Level 1	Level 2
1)	Layer Height	0.1 mm	0.3 mm
2)	Quality (boolean value): • Extra perimeters if needed •Avoid crossing perimeters •Detect thin walls •Detect bridging perimeters	0 (not active)	1 (active)
3)	Perimeters	2	5
4)	Solid Layers	2	5
5)	Fill Density	20%	50%
6)	Fill pattern	Rectilinear 	Honeycomb 
7)	Top solid infill (extrusion width)	85 %	100%
8)	Perimeters speed	20 mm/s	60 mm/s
9)	Small perimeters speed	20 mm/s	50 mm/s
10)	External perimeters speed	15 mm/s	40 mm/s
11)	Infill speed	60 mm/s	90 mm/s
12)	Extrusion multiplier	0.9 (= 90%)	1.1 (=110 %)
13)	Extruder temperature	180 C°	200 C°
14)	Retraction (Boolean value)	1 (active) (standard Slic3r values were used for the 6 parameters controlling the retraction)	0 (not active)

***Fig. 2** Gimax 3D S2 [7]*

The experimentation was run repeating each test three times, in order to increase the statistic validity of the results measured. All the runs were randomized to reduce the influence of external factors on the results. In order to reduce the number of prints required, the fractional design was carried out with a resolution III, which allowed the identification of main effects, although these may be confounded with two-factor interactions. 48 runs were totally performed.

The identification of most important parameters, to be selected for the second "detailed" fractional design, was performed by analyzing the results obtained at the end of the above-mentioned screening experimentation. Essentially, two tools were used to visualize and organize the data obtained [8]:

- the "Main Effect Plot", which allows the identification of the type of effect that a factor has on the considered output (positive/negative and its weight);
- the "Pareto Chart of the Effects", which shows the most influencing factors in order.

Both representations were generated directly using Minitab, after that measures and votes of the first 48 runs are populated in the software. The results were evaluated for each of the measured effects previously described (build time, XYZ dimensional accuracy, quality of overhang surfaces, small details quality on horizontal/sloped surfaces, surface quality on horizontal/sloped surfaces, overall quality, ability of printing holes and thin structures).

For each output, only statistically significant factors are considered and rated according to their influence on the measured effects; the rates obtained by each factor for all the outputs are then added to find the overall most influencing ones. In Tab. 3, the ranking of the overall most influencing factors is reported. Such classification eases the selection of the parameters to be included in the second detailed design. In order to build the ranking, every factor receives a point from 0 (its influence is under the statistical significance threshold) to 10 (the most important factor for the specific metric). The points assigned for each factor should be weighted considering the relative influence of each parameter (e.g. a parameter that is close to the statistical significance threshold should receive a low value even if it's the second most important factor for the considered metric). This operation is repeated for each metric evaluated in the experimentation (e.g. build time, surface quality, etc.). The points obtained in each category are then added together to build a single index that is used to rank the factors. The selection procedure could be, hypothetically, tailored to the specific needs of the user, e.g. introducing weights to increase/reduce the importance of a certain metric in the general ranking.

***Tab. 3** Ranking of the overall most influencing factors. Green factors resulted beneficial (for all the quality metrics) when set always to the same level.*

Position	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Factor	Layer Height	Quality	Fill Density	Perimeters	Extruder temperature	External perimeters speed	Small perimeters speed	Retraction	Infill speed	Extrusion Multiplier	Top solid infill	Perimeters speed	Fill pattern	Solid Layers
Score	49	41	25	22	20	16	14	14	12	10	6	6	5	3

The factors resulting beneficial for the measured effect when set always to the same level (colored in green in Tab. 3) can be excluded. In other words, these factors, once they are set to one of the two levels do not implicate negative effects. This is visible in the main effects plot, such as the one depicted in Fig. 3, which refers to the surface quality for the horizontal surfaces. All the identified factors, although fundamental, are not interesting for the present study because they can always be set to the identified value without imposing any compromise or negative effect to the FDM performances.

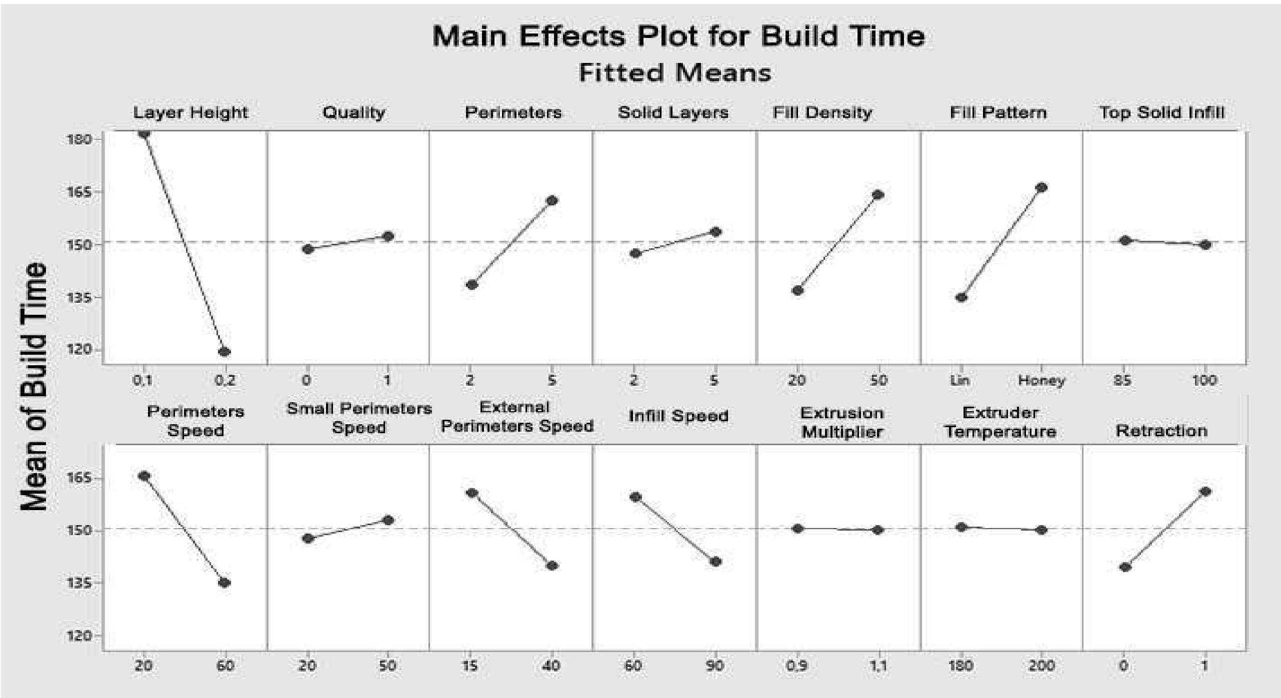


***Fig. 3** Main Effects plot for Build Time.*

4 Detailed Two-level Fractional Design

On the basis of the outcomes of the preliminary two-level fractional factorial design, five factors (out of the original fourteen) have been selected for a detailed experimental design. Such factors are reported in Tab. 4 along with the values set for the two levels (low and high).

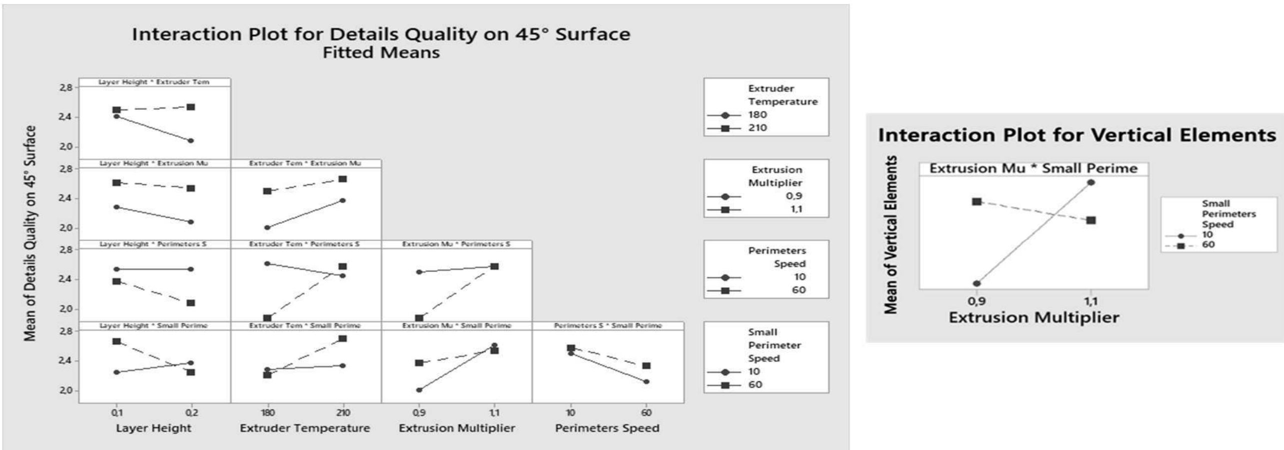
A two-level fractional design with resolution V, five factors and three repetitions for each run (i.e. a total of 48 runs) is therefore carried out. This allows to obtain a detailed description of the effects i.e. the identification of main effects and of two-factors effect with a good accuracy (this is due to the fact that they are contaminated only by higher-order effects, which are generally negligible).

Tab. 4 *Factors of the two-level detailed fractional design and their two-level values*

Factor	Low	High
Extruder Temperature	180°C	210°C
Layer Height	0.1 mm	0.2 mm
Extruder Multiplier	0.9	1.1
Perimeters speed	10 mm/s	60 mm/s
Small Perimeters speed	10 mm/s	60 mm/s

The results obtained at the end of the detailed two-level fractional design are summarized in Tab. 5 and Tab. 6 in order to provide a general perspective on the study. Tab. 5 shows the most influent factors for each analyzed output; Tab. 6 presents the levels that resulted as beneficial for the achievement of higher performances for each specific output. In a first phase, results obtained for each output are analyzed separately to identify relevant factors. The results on the *Dimensional Accuracy* for the three axes and the results for *Quality of Details* for the horizontal and sloped surface are left separated in order to identify possible discrepancies. The different mechanics of the FDM process on the three axes, moreover, does not allow to group together, at least as a first step, these dimensions. Only statistically significant results (using an $\alpha = 0.05$) are therefore taken into consideration; this brought to the elimination of the results of the dimensional accuracy on the Z-axis, which were under the selected threshold.

The results obtained for the *Dimensional Accuracy* of X and Y axes are similar, proving the equivalence of the mechanics of the process on the X/Y directions; the *Extrusion Multiplier* reasonably results as the principal factor for the dimensional accuracy; when it is set at the highest value, in fact, the print results more cohesive but less precise. Considering the *Details Quality,* different results were obtained w.r.t. the horizontal and 45° surface. For the horizontal surface, the most significant factor resulted to be the L*ayer Height*, which has a positive effect when set at the highest value. For the 45° surface, the most important factors are the *Extrusion Multiplier* and the *Perimeters Speed;* interactions between factors resulted particularly important for the *Details Quality* on the sloped features: their effects are showed in Fig. 4.



a) b)

Fig. 4 *a) Interaction Plot for Details Quality for the 45° surface; b) Interaction Plot for the Vertical Elements, limited to the Extrusion Multiplier/Small Perimeters Speed interaction*

Regarding the second-order interactions, the most significant are those between the *Extruder Temperature/Perimeters Speed*, which is the most important factor for the Quality of Details on the 45° surface, and *Extrusion Multiplier/Small Perimeters Speed* (Fig. 4b), which is the first factor for the *Vertical Elements.*

Tab. 5 *Ranking of the most influent factors for each effect: A – Layer height, B – Extruder Temperature, C – Extrusion Multiplier, D – Perimeters Speed, E – Small Perimeters Speed. For each effect, the color scale categorizes the factors from the most influent to the less ones (respectively from green to red). Combined effects (i.e. second order effects) are indicated with both the corresponding letters.*

	Vertical Elements	Holes	Details H	Details S	X	Y	Over-hangs	Overall Quality	Build Time
1	**CE**	**C**	**A**	**BD**	**C**	**C**	**D**	**A**	**D**
2	**C**	**D**	**AB**	**C**	**D**	**D**	**BD**	**C**	**A**
3	**BD**	**DE**	**BC**	**D**	**BE**	**AE**	**AE**	**AC**	**AD**
4	**A**	**E**	**B**	**CD**	**E**	**BE**	**AB**	**B**	
5	**E**	**BE**	**BD**	**AE**			**C**	**BC**	
6		**CD**	**AD**	**B**			**CE**	**D**	
7		**BC**	**DE**	**CE**			**BE**	**CD**	
8		**AC**		**BE**			**E**	**AD**	
9				**AB**					

Tab. 6 *Beneficial levels of the first-order factors for each effect.*

Factor	Vertical Elements	Holes	Details H	Details S	X	Y	Overhangs	Overall Quality	Build Time
Layer Height	high		high					high	high
Extruder Temperature			high	high				high	
Extrusion Multiplier	high	low		high	low	low	high	high	
Perimeters Speed		high		low	high	high	low	low	high
Small Perimeters Speed	high	high			low		high		

5 Conclusions

The present work aimed to devise an effective and easy-to-apply strategy for the characterization of any FDM machine. By following the procedure described in the text, a FDM user is able to perform a complete characterizitaion of their FDM machine by realizing a maximum of 96 prints of the custom-built specimen (available at [9]). As a result, the entire experimentation could be completed using approximately 2kg of material and 150 printing hours. Summing up, the presented procedure guarantees a simple yet effective characterization of any FDM machine with the use of limited resources. The methodology proposed is adaptable to the user needs both in terms of inputs (selected settings value to consider in the experimentation) and outputs (quality metrics).

On a general level, the results obtained by applying the proposed procedure could be used to draw guidelines to be integrated in the logic process flow of a 3D printing software. By exploiting the knowledge acquired on the specific machine studied, the slicing software could provide tailored printing settings in order to improve the performance of the FDM machine. Moreover, a set of relations and suggested values could be enforced by the software in order to maximize the outcome observed on one particular aspect. Such settings could also be suggested or changed automatically by the slicing software after examining the geometry of the STL model provided as input; for example, the identification of small details or thin vertical elements could be achieved fairly quickly by an algorithm examining the STL surface properties and the corresponding recommended settings could be enforced. The introduction of parameter selection strategies from the early design stage could allow for significant costs reductions, heavily reducing the time spent for multiple test prints and the associated waste of material. The results obtained during this study could lay the basis, if properly integrated with additional data gathered from similar researches, for an exhaustive mathematical model to describe and simulate the effect expected from a set of process parameters values given as input. The test model that has been designed and presented in the first part of this work could be a useful tool for FDM performance evaluation in future studies. The use of a standard model could, in fact, allow the gathering of a vast quantity of data on FDM process parameters that are comparable, overcoming the limitations of the present study (e.g. the use of a particular FDM machine, the effects introduced by environmental conditions) and increasing the statistical validity of the results. Future work will be addressed towards the development of a full response surface in order to improve the resolution and quality of the results; such data could be useful for the development of a reliable prediction tool; the development of a full response surface could allow a better description of non-linear effect, which are, de facto, linearized in a two-level fractional design.

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