

## Optimizing Fabrication Outcome in Low-cost FDM Machines. Part 1 - Metrics

Francesco Buonamici, Monica Carfagni, Rocco Furferi, Lapo Governi, Marco Saccardi, Yary Volpe  
 Department of Industrial Engineering of Florence, University of Florence – Via di Santa Marta 3, 50139, Firenze, Italy.  
 E-mail: francesco.buonamici@unifi.it, monica.carfagni@unifi.it, rocco.furferi@unifi.it, lapo.governi@unifi.it, marco.saccardi1@stud.unifi.it, yary.volpe@unifi.it.

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 focuses 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. Specifically, several effects are considered: dimensional accuracy, small details, overhang surfaces, ability of printing small holes/thin extrusions and overall quality of the prints. 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. The second part presents the characterization procedure, the statistical tools used in 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.

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

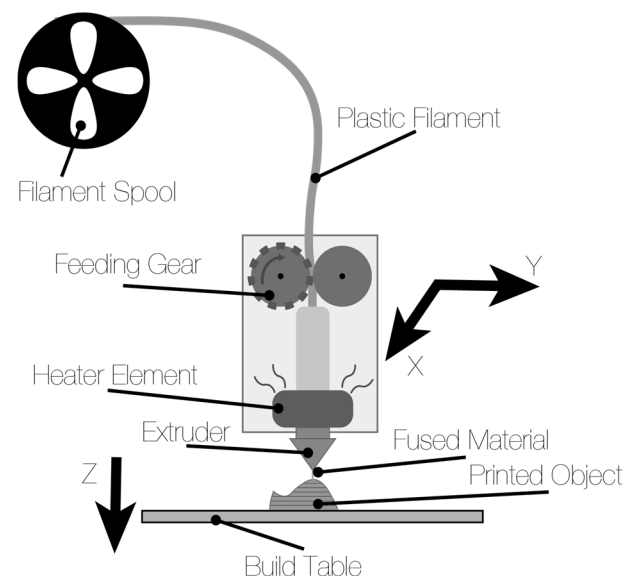
### 1 Introduction and background

Fused Filament Fabrication (FFF), typically referred to as Fused Deposition Modeling (FDM), is nowadays one of the most known and popular Additive Manufacturing technologies. The straightforwardness of the process, the wide range of plastic materials and low costs of 3D printers have allowed FDM to spread in a market characterized by both industrial realities and private users. Since the expiration of the main process patent in 2009 [1], in particular, prices for FDM printers have greatly reduced and a throng of various models of desktop machines has flooded the market, greatly increasing the percentage of home users. Although involving hot moving parts and molten plastic, the overall FDM process is, in fact, quite clean and safe even for untrained users; moreover, the production process is adequately managed by various 3D printing software systems, allowing the fabrication of the desired objects even to beginners, thanks to simplified GUIs.

Fig.1 shows a schematic representation of the FDM process: the raw material is fed in form of a plastic filament to a hot extruder, where is melted and forced through a nozzle. In the most common architecture, this element is responsible for X-Y movements, while movements on the z-axis are accomplished by the translation of the build platform. The object is created by depositing material on a series of layers of pre-determined thickness, following a set of instructions created by a 3D printing dedicated software.

While the general functioning of the process is basic, several parameters and factors contribute to the quality of the obtained output. The achievement of acceptable results on parts with elementary geometry, in terms of general quality of the produced prints, is usually simple and

predictable. Unfortunately, satisfactory models are difficult to obtain when dealing with complex parts (e.g. parts characterized by overhangs, bridges and fine details). Moreover, the introduction of additional user requirements and/or production constraints (e.g. “fast” productions, low material consumption, desired mechanical properties of the produced parts) is an additional challenge to confront with during the additive manufacturing process. Generally, the frustration caused by the umpteenth failed attempt at printing a rather complex part is a well-known sentiment across the “makers” community.



**Fig. 1** FDM process: basic elements and functioning

To partially solve the above-mentioned issues, industrial-grade FDM machines usually come with a pro-

proprietary software controlling the slicing and path-generation tasks. This allows for a more controlled process, as the machine path and control settings are determined taking into account known information about the system capabilities and performances.

Desktop solutions, on the other hand, rely on generic 3D printing software solutions (e.g. Cura, Slic3r, Simplify3D) that are not specifically tailored to maximize the efficacy of the printer. As a result, the lack of detailed info on the printer's capabilities needs to be counterbalanced by the user's experience: it is the user's task to choose a beneficial 3D printer setup for each print. As previously mentioned, on such 3D printing software packages a simplified GUI is commonly implemented allowing only a limited choice of printing profiles. Within such GUIs, only the most important parameters are left as editable by the user, hence reducing the complexity of the pre-processing operations. This is sufficient when dealing with simple parts, but it may negatively affect the realization of complex ones. In such cases, the user can consequently access to an "advanced" panel of settings and edit all the process parameters, controlling the entire system.

Depending on the 3D printing software, dozens of parameters (and options) can be set, each one of them influencing the overall FDM process and the quality of the 3D print. Accordingly, the seek for a satisfying set of parameters is a difficult task that is usually pursued by means of a trial and error approach, which obviously involves a significant investment of time, material and, ultimately, money. Additional uncertainties are introduced, considering desktop solutions, by the properties of the raw material, the characteristics of the printer and the specific geometry of the part that needs to be printed. Indeed, the high number of parameters makes difficult the certain identification of the effects ascribable to a specific factor and, even more, the study of combined interactions of parameters. In order to address this issue and, ultimately, improve the quality, efficiency and reliability of the FDM technology, several studies have been presented in the literature.

A vast part of the scientific work in the field is oriented to analyze how the principal FDM process parameters affect the mechanical properties of fabricated parts [2-9]. Many other studies are focused on the parameters effects on build time (e.g. [10-13]). It is worth noting that a minor effort has been spent on studying many other outcomes such as surface quality, dimensional accuracy, lack of defects on overhang surfaces, small details fidelity, etc. Nevertheless, such aspects are essential whenever the user needs to produce conceptual and functional models. It is important to note that private users, who constitute a large share of FDM users,

Quality-related aspects are somewhat overlooked by most researches at the state of the art and, whenever considered, only a very restricted set of process parameters are included in the experimentations (as in [13-17]), excluding those that are traditionally judged as less important. As an example, four parameters are considered in [14] (line width compensation, extrusion velocity, filling velocity, layer thickness) to build a model describing the

warp deformation and dimensional errors that are observed on a series of printing tests. Moreover, as reported in [10], the seek for the optimal settings of parameters is typically carried out by considering each effect individually (e.g. the quality of overhang surfaces). For instance, the effects induced by a single parameter (i.e. temperature of the printing pad) are described in [18]. Despite the mentioned approaches are useful for assessing the behavior of FDM process, the setting of a limited number of parameters is a condition far from reality applications, where the user needs to find a compromise setting solution able to simultaneously satisfy multiple requirements. In other words, to date little to any studies have been addressed to the investigation of the single and combined effects of FDM process parameters from a "wide" perspective i.e. by considering a vast population of both inputs and outputs.

Considering desktop FDM machines, the general applicability of the results presented by the mentioned studies is limited; this is due to the great variety of machines: very different performances and characteristics can be observed and measured in different models. As a consequence, results obtained on a particular machine, or even a brand of machines, cannot be extrapolated to all cases with certainty.

To overcome the above-mentioned drawbacks, this two-parts work proposes a procedure for the experimental investigation on the effects of a wide selection of FDM process parameters on the quality of 3D printed parts.

Seven different metrics are considered to describe the overall quality of produced 3D prints: build time, dimensional accuracy, small details, quality of overhang surfaces, ability of printing small holes, capability of printing thin vertical elements and overall quality of the print. To contemporarily evaluate the above-mentioned metrics for any printing setup, a test model has been appositely developed. Such a test model is characterized by a set of features that, once assessed, provides a reliable measure of the printed model quality. Nonetheless, the proposed method can be easily applied to any other kinds of FDM-based machine giving for assured the possibility of varying the same process parameters. By implementing the procedure presented in this paper, FDM users will be able to characterize the performances of their FDM machine and tune the printing parameters in order to optimize the produced result. Moreover, this process could be specifically tailored to optimize a particular output of interest (e.g. build time vs. dimensional accuracy, quality of overhang surfaces). As a result, the procedure is scalable and adaptable according to the user specific needs and goals. The characterization is achieved with a series of test prints, analyzing the results obtained as the printing settings change.

A correct evaluation of the print quality is the first and most important aspect that needs to be addressed in order to achieve the described goal. Accordingly, the development of a reliable and effective measurement procedure for the parameters of interest is described in this paper. The second part of the paper, on the other hand, will focus on the description of the actual procedure that a potential

user should follow in order to characterize their FDM machine, highlighting the software tools and materials as well as the steps to follow.

## 2 Materials and Methods

With the aim of proposing a practical method for the evaluation of the effects of several FDM parameters on the quality 3D printed objects, the first step that needs to be carried out is the definition of a number of metrics to assess the quality of parts produced using the FDM process (quality parameters). For each 3D printed model obtained using a given setting of the 3D printer, such parameters can be measured and the obtained value is used for the quality assessment. In particular, seven metrics have been defined, as described in Section 2.1, together with an appositely devised specimen and a quantitative/qualitative measurement procedure which is presented in the following.

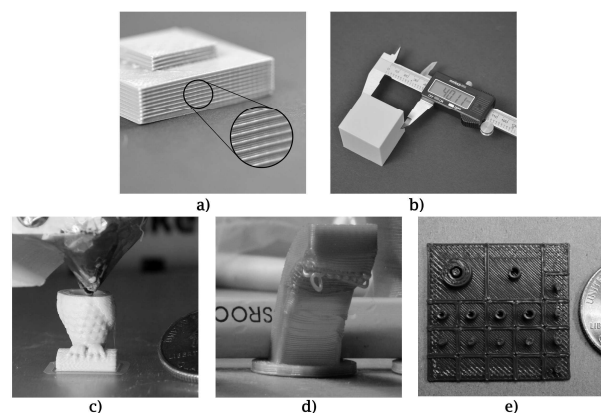
### 2.1 Definition of quality metrics

With the aim of investigating the effect of different process settings on the quality of manufactured product, the first step consists of the definition of quality metrics i.e. a set of parameters whose value “measure” the performance of the FDM process. Derived both from the analysis of the state of the art [2,3,10,12,20,21] and from common practice suggested by experts working on FDM applications (some of the effects that are typically observed on FDM parts are shown in Fig.2.), the metrics adopted for this study are:

- **Build time** – this is among the most important aspect considered by users when confronting with 3D printing. Both the layer height and the nozzle dimension mostly influence it.
- **Dimensional accuracy on XYZ directions** (w.r.t. the machine axes) – the dimensional accuracy of the manufactured parts is a fundamental element that must be considered when designing a part, regardless of the chosen fabricated technology [22]. In 3D printing, and in FDM in particular, the knowledge on the performances that are guaranteed by desktop printers is still limited; when printing parts that need to precisely interact and fit with other elements, satisfying results are typically achieved by a trial-and-error approach.
- **Accuracy of small details** – small features and details are important in lots of applications. It is widely recognized that the principal factor influencing the level of details producible is the nozzle size, which determines how much material flows out of the extruder. A small diameter allows for a higher precision but greatly increases the printing time. Since this study aims at finding the most important and non-trivial factors that contribute to the accuracy of the process

(also in the printing of small details) the nozzle size has been left out of the analysis, as described in the next section, to discard its obvious contribute on this aspect.

- **Quality of overhang surfaces** – the ability to print very sloped surfaces has an enormous impact on the usefulness of FDM technology and reduces the need for supports. Typically, a  $45^\circ$  overhang is taken as maximum angle for the surfaces that can be printed without the need of supports, allowing each layer to expand a little outside the limits defined by the previous layer. Although being essential in multiple situations, in fact, supports introduce problems like deterioration of surfaces, local defects, a higher printing time and the use of additional material.
- **Ability of printing small holes** – to the best of the authors’ knowledge, this aspect has never been covered before by similar studies. The *ability of printing small holes* is, in some way, related to the *accuracy of small details* but specifically oriented to measure the ability of leaving void spaces in the printed object as close as possible to the original designed object.
- **Capability of printing thin vertical elements** – this is especially important for the printing of support and infill structures, which are usually built with a single wall.
- **Overall quality of the print** – this last metric is meant to qualitatively describe the obtained model. The evaluation produced by considering only the aforementioned metrics may lead to a sort of “loss of perspective” in terms of quality assessment. Therefore, a more qualitative analysis is introduced.



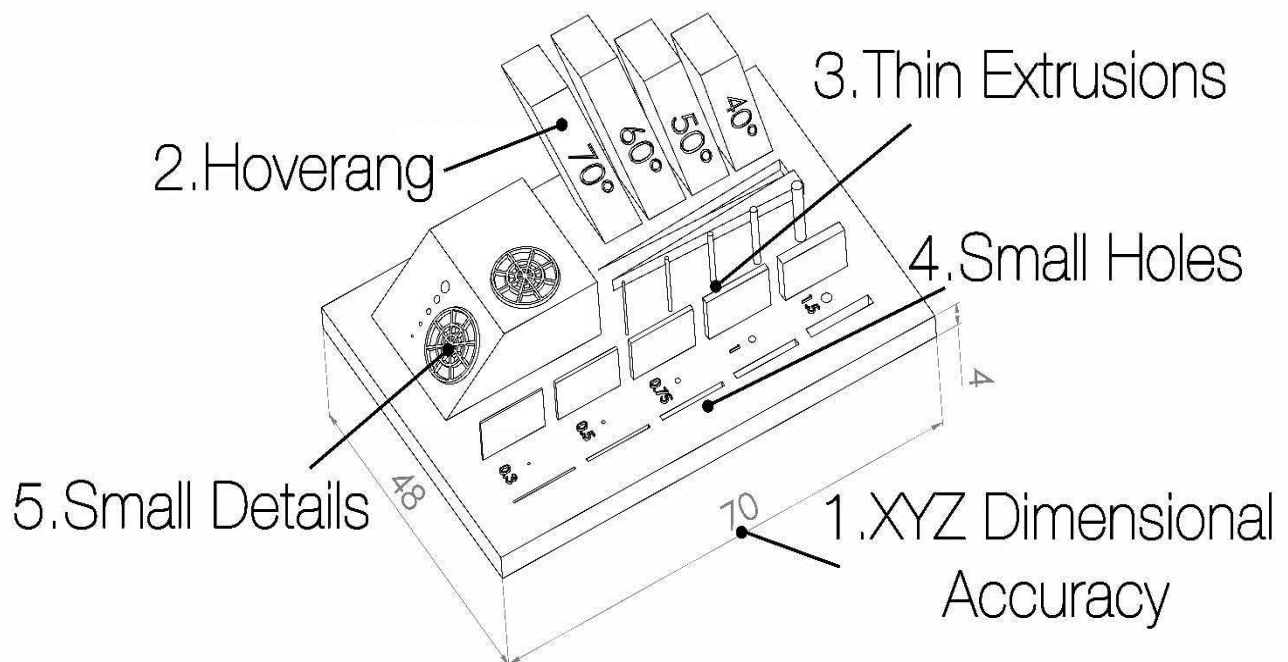
**Fig. 2** Some of the effects evaluated in this study. a) overall quality of the print, b) dimensional accuracy, c) overall quality of the print, d) accuracy of small details, e) quality of overhang surfaces, f) ability of printing small holes

The set of seven metrics previously formalized can contemporarily be assessed for a given 3D printing setting by (1) designing a suitable specimen (see Section 2.2) and (2) applying a rigorous measurement procedure (see Section 2.3). The adoption of the measurement procedure proposed in the following text is recommended, as it allows for a reliable and robust result; moreover, the specimen described in the following section has been specially designed in order to sustain the proposed measurement procedure. Nevertheless, according to the measurement tools available to the procedure user and their needs, a different measurement procedure could be hypothesized.

## 2.2 Specimen design

To assess quality metrics, it is necessary to design a specimen characterized by geometric features that enable and facilitate the measurement on the obtained model. Therefore, a custom test model was appositely designed using a CAD modeler (i.e. Solidworks®). Such a model, made available to future users at [23], has been conceived trying to assure a limited printing time (in order to reduce the total experimentation time). The specimen is composed by the following features, enumerated as depicted in Fig. .

1. A 48x70x4mm base, which has the double purpose of both offering a support for all the desired geometric features (hereby described) and providing easily measurable dimensions to evaluate the dimensional accuracy of the process;
2. Four prism elements, with slopes of 40-70 degrees w.r.t. the vertical plane, to evaluate the 3D printer ability and precision in reproducing overhang surfaces;
3. Two sets of vertical elements (one set with rectangular and the other with circular basis); such elements are characterized by widths from 1.5 mm to 0.3mm to assess the ability of printing progressively thinner structures.
4. Two sets of cuts in the model base, rectangular and circular, with dimensions varying from 1.5mm to 0.3mm; these elements are used to assess the ability of leaving clean and well-defined openings having progressively smaller dimensions.
5. Two web-like structures built with three concentric circles of diameters 2.5mm, 5mm, and 9mm; the circles are built with wall structures that are 0.6mm wide at the base, and extruded for a total height of 0.5mm with a draft angle of 16°. Additional ribs of the same geometry are built in order to define a more complicated pattern. Such geometry becomes difficult to print moving towards the center of the circles and it therefore can be used as an indicator of the aptitude of the tested setting to obtain clean and precise details. The structure is replicated on a 45° sloped planar surface to test the same behavior on inclined surfaces as well.



**Fig. 3** The test model and its composing geometrical features, dimensions in mm.

Additional geometric features, not exploited in the present study, are included in the proposed 3D model; such elements (i.e. horizontal holes of different diameters, thin triangular slots and extrusions, horizontal and sloped planar surfaces) could be useful for future experiments. Considering that such features have a limited

impact on the printing time, these are printed also for performing the present study, even if they are not used to evaluate the effect of different 3D printing settings. The number of features introduced for the evaluation of each specific metric has been pondered to ease the measurement of the characteristics of interest. Several quality me-

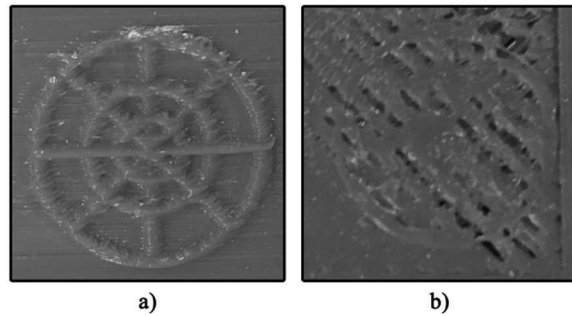
metrics considered in this procedure, in fact, cannot be quantitatively measured without advanced tools; accordingly, a system based on visual assessment and identification of successfully-built geometric elements has been devised. By observing the specimen's features, the user is able to ascribe a score to the quality metrics that, otherwise, wouldn't be easily assessable.

### 2.3 Measurement procedure

It is worth noting that, prior to perform the entire characterization procedure, a proper calibration of the FDM machine is always required in order to remove significant errors that could affect the basic setup of the printer. For instance, the correct positioning between the printer bed and the guide rails controlling the extruder movement should, at least, be confirmed. Possible planarity issues of the bed surface could be compensated by introducing a support structure (i.e. raft) of at least 5 mm in the first printing layers.

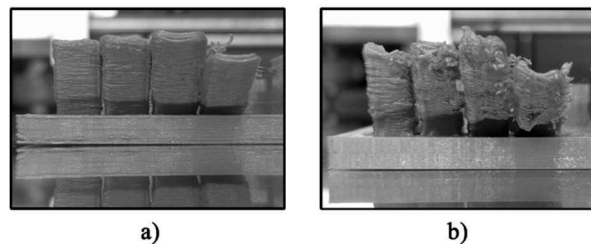
Once a specimen is manufactured by using a given setting for the FDM process, it is necessary to properly measure its features to assess the defined quality metrics. Firstly, the specimen has to be properly constrained to a flat surface (a proper measurement table would be the ideal choice) in order to avoid significant errors in the evaluation of the results. Referring to the metrics defined above, measurements are carried out as follows:

- **Build time.** Measured in minutes as the overall fabrication time.
- **Dimensional accuracy on XYZ directions.** Twenty measures, repeated in different points of the model base's width, depth and height, need to be taken using, for instance, a centesimal caliper for each direction. Measured points can be then compared with the virtual model corresponding values to obtain the actual deviation. Finally, the mean deviation, on the ten measures, provides the accuracy for X, Y and Z directions.
- **Accuracy of small details.** This metric is evaluated both on horizontal surfaces (detail H) and on sloping surfaces (detail S). Detail H is evaluated using a score between 0 and 3. This score is qualitatively assigned examining the web-like structure extruded from the horizontal planar surface of feature #5 in Fig.3Fig. . The criteria to assign the score is as follows: half a point has been granted for each partially-built circular crown, and a point has been assigned for perfectly built ones; finally, zero points have been assigned to badly built circumferences. Detail S is assigned using an analogous score-based procedure this time taking into account the web-like structure laying on the sloped planar surface (feature #5 in Fig.3Fig. ).



**Fig. 4** Accuracy of small details, best (a) and worst (b) results

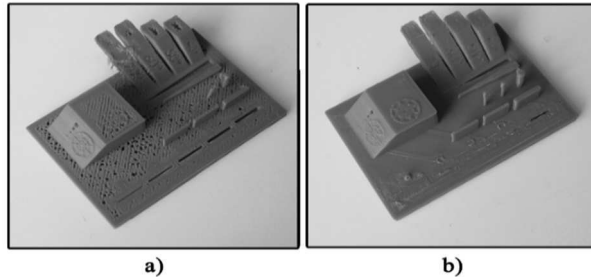
- **Quality of overhang surfaces.** This metric is evaluated in a qualitative manner by assigning a number between 0 and 4 correlated with the number of sloped elements correctly built in the evaluated run (see Feature #2 in Fig.3). One point is assigned for each element perfectly built, and half a point for elements extruded with some defects; zero points are assigned when an overhang surface is "badly built" or even absent. An example of "best" and "worst" results obtained for overhang surfaces are in Fig.5; in the two exemplificative cases the best case is marked with a value equal to 4 and the worst with a value equal to 1/2.



**Fig. 5** Overhang surfaces, best (a) and worst (b) results obtained in the study and used as reference to build a measurement scale

- **Ability of printing small holes.** A score between 0 and 5, related to the number of correctly realized holes, is assigned to characterize this metric. In particular, 1 point is assigned for each hole correctly realized. A 0 value is assigned in any other case.
- **Capability of printing thin vertical elements.** A score between 0 and 5 describing the ability of realizing slender structures oriented along the z-axis of the machine is assigned. For the evaluation of this parameter, 1 point is given for each element correctly realized.
- **Overall Quality.** A score between 0 and 5 is assigned in a qualitative way by evaluating the

general quality of the model, its solidity, integrity and cleanliness of surfaces, summing up the overall result obtained in generating all the designed features. Examples for the worst and best results obtained (marked with a 0 and 5, respectively) are visible in Fig. 7.

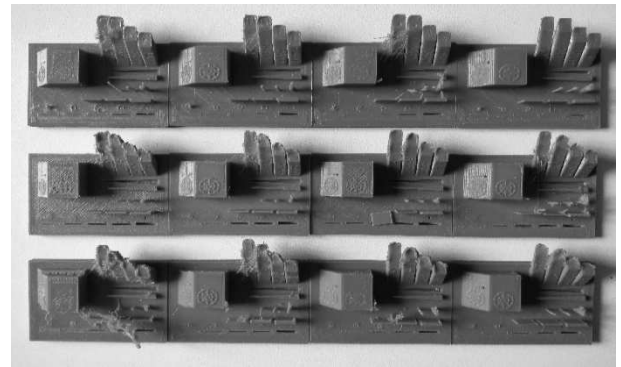


**Fig. 7** Overall quality best (a) and worst (b) results. These were used as landmarks for the definition of an “Overall Quality of the print” measurement scale

The authors also experimented on the evaluation of the surface quality of the planar surfaces of the specimen. A possible measurement procedure, based on the acquisition of multiple points on planar regions and the subsequent evaluation of a best-fit plane by means of a contact probe mounted on a Hexagon Absolute Arm [24] was tested. Unsatisfactory results were obtained in the preliminary tests: a very low repeatability was observed during the measures and the corresponding processed data resulted as statistically not significant within the fractional design. The measurement of surface roughness or the characterization of the surface texture (ISO 4287:1997), rather than an estimate of the surface planarity, could be considered as alternative strategies. Generally, the seek for the best index to measure the surface quality of AM parts is not trivial, as proved by recent studies on the topic [25]. Moreover, the correct quantitative evaluation of this parameter requires advanced measurement tools which are typically not available to private users. Accordingly, the surface quality observed in the printed models was considered within the *Overall Quality* metric in this study.

### 3 Results and Conclusions

The measurement methodology has been tested by four different non-expert users, evaluating the quality of the 12 models depicted in Fig. 8. It must be noted that a certain degree of subjectivity is involved in the point assignment mechanism even if, for most metrics, the user is guided by the number of geometric features correctly built on the specimen. As a result, slight differences have been observed among the results. However, the measurement procedure has been proved suitable for the specific goal of the study: after a short training, all the users have easily applied the above-described steps and have been able to achieve valid measures on all the metrics described in the paper. Moreover, the goal of the proposed methodology is not to achieve absolute measurements for a series of physical quantities, rather provide a tool for the comparison of multiple quality parameters between printed objects.



**Fig. 8** –3D printed models used to evaluate the measurement procedure

This paper is the first 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. Furthermore, the results obtained applying the proposed strategy allow a custom optimization of the entire FDM process, tailored on the specific features and performances of any FDM machine. Specifically, a simple yet effective measurement procedure is presented in this paper. The proposed procedure does not impose any advanced software or measurement tool to the user; as a result, the entire methodology can be applied even by users belonging to the low-end market sector, which typically do not have access to advanced instrumentation.

In the 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 analysis, making use of two fractional two-level designs, will be proposed to carry out the experimentation. The devised methodology is based on DOE principles and makes use of basic statistical tools. The entire procedure will be presented in the second part of the article with reference to the “S2” desktop FDM printer produced by Gimax 3D with propaedeutic purposes.

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