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A methodology for evaluating the aesthetic quality of 3D printed parts

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Abstract

Nowadays, 3D printing is recognized as one of the key technologies that enables the distributed manufacturing adoption. However, inexperienced people might perceive this technology as far from easy user-usability because of evident aesthetic defects on 3D printed parts.
In this paper, an indicator-based methodology is proposed for the assessment and the ranking of the aesthetic capability of 3D printers by evaluating the ability of a 3D printer to reproduce a reference part without defects. The reference part includes several geometric features that characterize most of as-built aesthetic defects. In addition, a benchmarking analysis was carried out to show an example of the methodology applied to three different machines.

Keywords: 3D printing; aesthetic quality; benchmarking; indicator-based methodology; robustness analysis.

1. Main text

In contrast with the current economic models, the democratization of the production is deemed one of the cornerstones of the so-called third industrial revolution [1]. Similarly to the advent of the personal computer, the third revolution is making small production machines accessible to a large number of people in the form of a personal fabricator (PF) [2]. This term defines the ideal machine for 3D printing objects that integrates case, sensors, and logic [2]. Technological development is still far from the PF and the revolution is essentially based on the large-scale application of certain enabling technologies that have been defined as qualifying for the scope, such as internet and 3D printing [1-3]. 3D printing is the popular and commercial term of additive manufacturing (AM) systems based on material extrusion that was originally patented as fused deposition modelling (FDM) [1]. In material extrusion, a nozzle heats and extrudes a thermoplastic filament to build an object [4] directly from a virtual 3D model. During the extrusion, the filament is deposited over the previous built layer. A thermal process similar to that occurring during welding ensures the adhesion and continuity between the previous layer and the new one.

The first FDM system was developed by Scott Crump that cofounded Stratasys company in the late 1980s [2, 3]. However, the recent expiration of the main FDM patents has promoted the development of a large number of low-cost 3D printers that are currently available on the market. According to the pillars of the third industrial revolution, the development of new low-cost 3D printers is benefiting from open-source systems as well as sharing of information to accelerate the process development and optimization. Moreover, many people are attracted by the opportunity to design and manufacture their own products with higher engagement [4]. Unfortunately, the real perception of an unprofessional user is that the technology is often far from the expectations of easy production. In fact, the poor quality of certain 3D printed features can be perceived as a failure of the technology.

For this reason, aesthetics is one of the key dimension of the perceived quality of a product [5, 6]. In fact within a ser-

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oriented approach [7], quality is measured as the ability of the part to meet customers' expectations [7, 8]. This concept is largely applied to plastic parts produced by traditional injection molding [9-11], in which functionality and aesthetics requirements are considered as equally important. In the literature, several benchmarking models have been proposed to compare 3D printers in terms of dimensional and geometric accuracy [12-25] of as-built artifacts sometimes using ISO IT grades [26]. However, there are no benchmarking studies about the aesthetic quality of 3D printed parts because aesthetics is a qualitative and subjective characteristic, that is not as easily quantifiable as dimensional measurements.

The aim of this work is to fill that gap by proposing a methodology for evaluating the aesthetic quality of the 3D printed parts. The methodology is based on an innovative reference part that includes several features that are representative of typical aesthetic defects that contribute to jeopardizing the perceived quality of 3D printing. An indicator called Aesthetic Quality Index (AQI) is defined to assess the dimension of the aesthetic quality. Finally, a benchmarking of three different machines analysis is carried out using the proposed AQI.

2. Print Quality overview

As concerns the aesthetic quality of 3D printed parts, most common manufacturing defects of parts have been collected from authors' experience and through free troubleshooting guides [27-29] that are available in the web.

Fig. 1 depicts the most common issues that could be noticed in a printed part [27-29]. These defects appear for specific geometries that are different for each issue and from each other. The definition and the most common causes of the issues are listed here below:

- Overheating (Fig. 1a) occurs when the next layer is deposited while the polymeric material of the previous layer is not cold yet.
- Gaps between contours and infill and gap into infill line (Fig. 1b) despite the infill strategy is set to 100%.
- Stringing (Fig. 1c) is referred as thin plastic filaments that are left behind by the extruder during the deposition of the material.
- Layer Separation and Splitting (Fig. 1d) are mainly due to a too low value of the extrusion temperature.
- Skipped layer (Fig. 1e) is caused by mechanical problems in the driving mechanism of filament that prevents the material from being extruded and deposited correctly.
- Whiskers that are left on unsupported overhangs (Fig. 1f). Overhangs are all features where the added layers could not be correctly supported by the previous layers. Without any support structure, the machine fails in printing the overhanging features correctly.
- Gaps in thin walls (Fig. 1g) are present because the width of the wall is not a whole number multiple of the diameter of the nozzle.
- Blobs and zits (Fig. 1h) are referred to an excess of material that can be observed at the starting or final points of a closed path within the same layer.

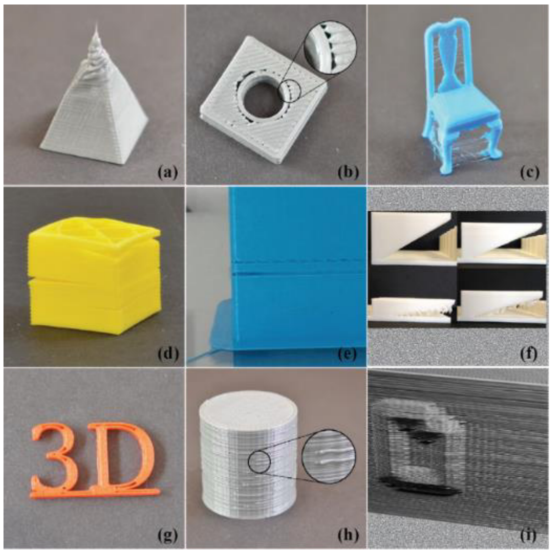


Fig. 1. (a) Overheating effect (b) Gaps between contours and infill and gap into infill line (c) Stringing (d) Layer separation (e) Skipped layer; (f) Whiskers (g) Gaps in thin walls; (h) Blobs and zits (i) Ringing [26-28].

- Ringing (Fig. 1i) which is a wavy pattern that appears on the printed surface.

3. Reference part

The design of the artefact was driven by the necessity of reproducibility of the defects that were mentioned and classified above. In addition to this, unlike other artefacts that were designed to avoid the need for supports [22], the proposed reference part requires the use of support structures, which are removed manually before the slicing phase. Therefore, the machine is forced to build the part without using of supports.

The proposed artefact was designed to fit into the building volume of most of the low-cost FDM machines and its overall dimensions are 48x34x33 mm^3 with a volume of 12,860.42 mm^3. The size was chosen for the part not to take a long time to build and not to require a large amount of material. For the two most common materials in 3D printing, which are ABS and PLA, 14 g and 17 g are respectively needed for the fabrication of one replica of the reference part.

The artefact has a rectangular base that is 5 mm thick to prevent deformation after separation from the building platform. The geometric features of the part were rationally organized as shown in Fig. 2. Thus, the part must be 3D printed using the orientation wherein the largest flat surface of the base lays on the printer bed and the Z axis (Fig. 2) is aligned to the build direction of layer deposition.

The geometric features are identified singularly or in groups by letters as described in Table 1

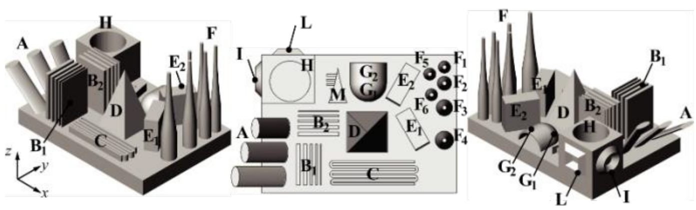


Fig. 2. Reference part.

Table 1. Description of the nominal geometry (CAD model) of the reference part.

Feature	Description and note
A-Group	Thin walls titled of 30 degrees, 40 degrees and 50 degrees with respect to the horizontal plane. In order to have thin walls without corners or sharp changes of direction of the extrusion head, the cross section is elliptic with major and minor axes equal to 5 mm 2 mm respectively.
B1 and B2	Groups of vertical walls with a rectangular base and a height of 5 mm. Five walls are aligned to the x-axis, while other five blocks are aligned to the y-axis. Each wall is separated from the others. While the width of 10 mm is the same for all walls, the thickness decreases in the sequence 1 mm, 0.8 mm, 0.6 mm, 0.4 mm and 0.2 mm.
C	Series of walls that are 2 mm high. The thickness of the walls is equal to 0.5 mm, while the distance between each wall couple increases from the wall close to the external edge of the inner wall. The distance varies in the sequence 0.3 mm, 0.40 mm, 0.50 mm, 0.60 mm, 0.70 mm. In order to avoid sharp changing of direction of the extrusion head, a radius connects the walls according to the distance between two adjacent walls. The resulting shape is similar to a snake.
D	Pyramid with a square base with an edge of 10 mm and walls tilted of 75 degrees with respect to the horizontal plane. As a result, the pyramid is 18.66 mm high.
E- Group	Parallelepiped blocks that have a 4 mm x 10 mm rectangular base. The side walls of the blocks are not aligned with the main axes and side faces of the artefact base. In particular, the vertical symmetry plane of block E_1 is titled of 60 degrees with respect to the x-axis, while the one of block E_2 is titled of 30 degrees to the same axis.
F-group	Pattern of pillars, which are 28 mm high. Each pillar has a cylindrical base with a height of 8 mm and the diameter of each cylinder differs from the others. The four pillars from F_1 to F_4 are closer to the external edge of the part and have a top diameter that increases with the sequence 3 mm, 3.50 mm, 4 mm and 4.50 mm. The pattern is organized so that the distance between the pillars' bases rapidly increases to 0.75 mm, 2.25 mm and 3.75 mm. On the other hand, the pillars F_5 and F_6 in the second column have the same geometry of the pillar F_1 (the one closer to the external edge) and their base is positioned as follows. F_5 has a distance of 4 mm from F_1 and 4.25 mm from F_2, while F_6 has a distance from F_2 equal to 4.25 mm and 4.50 mm from F_3. As a consequence, F_5 and F_6 result misaligned of 0.42 mm and with a distance equal to 5.08 mm. The upper part of each a pillar is a solid of revolution with the same axis of the cylinder at the base and an arc of circumference as a profile. The radius of arc varies with the diameter of the base so that the circular area on the top is the same for each pillar, with a diameter equal to 1 mm. The distance between each pillar and the others is different for each couple of pillars and varies along the building direction.
G-group	Arched bridge (G_1) with a radius of 4 mm and a thickness of 0.5 mm as the walls of feature C. In addition, a convex hemisphere (G_2) with the same radius and thickness is annexed to the bridge.
H	Parallelepiped with a base of 13 x 11.90 mm^2, a height of 12 mm and a 10 mm hole. The axis of the hole is placed in such a position that the distance between the circle and each vertical face of the block is different on each side. In particular, the minimum distance between the hole and the vertical surfaces of the cube changes anti-clockwise in the sequence from the bottom 0.4 mm, 1 mm, 1.5 mm, and 2 mm.
I and L	External surfaces of the feature H are formed as low reliefs with a square geometry I with an edge of 8 mm and a circle having a diameter of 9 mm. Each low relief is located in the centre of vertical faces of the H block. The cross section of the low reliefs along the yz plane is an isosceles triangle with a base of 3 mm, while the edges are 2.12 mm long. Since the angle between the vertical base and the edges is 45 degrees, these geometries should not be considered overhangs and do not require the need for support structures.
M	Prismatic block with a triangular base. The longer edges of the triangle are the part of an arc of a circle with radius equal to 41 mm so that the distance between the edges decreases rapidly up to zero through a length of 8.50 mm. The solid lines close to the geometry are located at different distances of 0.50 mm, 1 mm and 1.50 mm from the edges of the triangle.

4. Aesthetical quality evaluation

The criteria for the evaluation of the quality of the reference part replicas are classified as pure Aesthetical (A), pure Technical (T) and Technical and Aesthetical (TA) according to whether the criterion influences only the aesthetic or technical quality of the 3D printed part or both of them. The utility of each geometric feature of the artefact is summarized in Table 2 according to the selected criteria.

The assessment methodology is based on the definition of a unique composite indicator that can be used to summarize the aesthetical quality of a 3D printed part. The composite indicator is obtained by combining a set of underlying indicators and it is employed for the comparison and ranking of different 3D printing machines. However, since the use of a composite indicator results in a loss of information [30], the underlying indicators must be used to draw proper conclusions [31] about the causes of 3D printing defects in the artefact replicas.

The composite indicator is built as follows. In the first step, the criteria to be evaluated were specified and the relative indicator was defined (Table 2). According to the differentiation between technical and aesthetic criteria, the underlying indicators include objective measurements as well as subjective ones. Objective measures refer to the capability of a 3D printer to reproduce specific features under prescribed conditions as the absence of support structures. Subjective indicators are defined as information that includes some kind of a subjective component [32], such as a personal evaluation. Objective measurements are typically related to technical criteria, whereas subjective ones relate to aesthetics. However, since this paper aims to present a preliminary study on the aesthetical quality of parts produced by 3D printers, the pure technical criteria are not considered.

As far as the subjective evaluation is concerned, the indicators are defined on an ordinal scale on three levels "Low", "Medium" and "High". "Low" represents the lowest score and the poorest quality for the analysed feature. An arbitrary numerical codification is introduced to allow for an easy comparison of the 3D printers. Score 0 was assigned to level "Low", score 1 to "Medium" and score 2 to "High". Details about the assignment of the subjective level and score to each feature of the reference part are included in Table 3.

The total score for the proposed reference part is defined by the Aesthetic Quality Index (AQI) that is given by:

$$AQI = OH + GACI + STR + DEL + NOWH + NOSUP_{bridge} + NOSUP_{shell} + BL + RIN \quad (1)$$

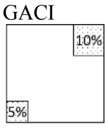
According to the definition given for each underlying indicator, AQI is still defined on an ordinal scale. AQI can assume values ranging from 0 to 18, where 0 is the worst

.

Table 2. Classification of the part features representing the analysed issues and corresponding indicator.

Criteria	Type	Features	Indicator
Analysis of overheating	TA	Peak of pyramid H and peaks of pillars F	OH
Gaps between contours and infill and gap into infill line	TA	Parallelepiped E_1 and E_2; top surface of block H and block M	GACI
Difference between the number of gaps in the layers between contours and infill and gap into infill line as a function of orientation	T	Parallelepiped E_1 and E_2, Cube H	-
Minimum thickness of infill between inner and outer contour	T	Block H	-
Stringing	A	Pillars F	STR
Layer Separation, Splitting and skipped layer	TA	Parallelepiped E_1 and E_2, Cube H	DEL
Capability to build overhangs without supports	T	A	-
Capability to create unsupported features without whiskers	A	A and G_1	NOWH
Capability to build bridge without supports	TA	G_1	$NOSUP_{bridge}$
Shell effect due to a thick unsupported convex feature	TA	G_2	$NOSUP_{shell}$
Minimum thickness	T	B_1 and B_2	-
Gaps infill in thin walls	T	B_1 and B_2	-
Differences from building the same feature along different directions	T	B_1 and B_2	-
Minimum gap between features	T	Feature C	-
Blob effect	A	Surface of pyramid D; Cylindrical surface at the base of the pillars; upper part of pillar F	BL
Ringing	TA	Feature I and feature F	RIN

Table 3. Rules to assess the underlying indicators.

Indicator	Features	High 2	Medium 1	Low 0
OH	D	No overheating effect, the peak of D is similar to the ideal shape	The peak was built, but it is partially deformed	The peak is very different from the ideal shape
GACI 	E1 and E2 H and M the base of the reference part	Gaps are absent or occupy less than 5% of the total surface and/or only thinner walls show holes	Gaps are visible and occupy more than 5% but less than 10% of the total surface; difference in terms of hole quantity are noticeable on the features E1 and E2; gaps between inner surface and contour are noticeable on the feature H	Holes are visible also in the base of reference part and/or their presence is greater than 10% of total surface
STR	F	Very limited stringing effect is noticeable	The stringing effect is significant only in the lower part of pillars F	Stringing effect is present across all pillars F
DEL	E1 and E2 H	No layer separation, splitting and skipped layer are noticeable	Only one layer was skipped and/or just one splitting between layers is noticeable	More than one layer was skipped and/or more than one splitting between layers is noticeable
NOWH	A	No whisker is present	Whisker is present only in the wall which is 30° tilted or the features that should be unsupported are supported because it was not possible to deactivate the function for the supports in the slicing software	Lots of whiskers are present in the features
$NOSUP_{bridge}$	G1	The arched bridge is well reproduced without defects	The arched bridge shows missing part on the top and/or defects	The arched bridge is collapsed or supported because it was not possible to deactivate the function for the supports in the slicing software
$NOSUP_{shell}$	G2	The hemisphere is well defined without holes	Hemisphere is imperfect and small gaps are present, but it is not collapsed	Hemisphere is collapsed
BL	D, F	No blob effect is present	Blob effect is present only in the upper parts of the pillars F and the pyramid D	Blob effect is present along all surfaces of the pyramid D and along the pillars F
OH	D	No overheating effect, the peak of D is similar to the ideal shape	The peak was built, but it is partially deformed	Ringing effect is noticeable for both the features L and I

score that represents the lowest aesthetical quality for a 3D printed replica of the artefact. The maximum score 18 corresponds to a limited number of imperfections for a high level of perceived aesthetic quality.

5. Benchmarking

The use of the proposed methodology is illustrated by evaluation of one replica of the reference part fabricated by means of three different 3D printers. The three compared FDM machines are available at the Rapid Manufacturing Laboratory (RMLab) of the Department of Management and Production Engineering of the Politecnico di Torino. The first 3D printer is the Makerbot Replicator 5th generation, which uses a single extruder. The second machine is the Dimension Elite by Stratasys, which has two extruders that are fed with ABS build filament and with soluble support Laboratory (RMLab) of the Department of Management and Production Engineering of the Politecnico di Torino.

The first 3D printer is the Makerbot Replicator 5th generation, which uses a single extruder. The second

machine is the Dimension Elite by Stratasys, which has two extruders that are fed with ABS build filament and with soluble support material respectively. The third 3D printer is the A4 model by 3ntr which comes with three extruders in the v3 version.

Starting from the same STL model of the part, the pre-processing and slicing operations are carried out using different slicers and different printing parameters. The results of some analysed criteria could depend on the set of parameters chosen for the 3D printing process. For this reason, the process parameters were set to the "default" value inside the slicing software provided with each 3D printer.

The 3nrt A4 is the only open-source machine, while the other two printers have their own proprietary slicers, Catalyst Ex® for the Dimension Elite and MakerBot Desktop® for the Replicator, thus the numerical control code is closed to the user. Nevertheless, the use of different parameters is imperative since each machine has a different configuration (filament diameter and nozzle size), so the set of process parameters should be specific. Table 4 resumes the 3D printing parameters that were used for the fabrication of the reference part replica on the three machines. After fabrication, each replica was then evaluated by one tester.

5.1. Results

Fig. 3 shows the printed reference parts and details of the manufactured features where the aesthetical defects of the part can be noticed.

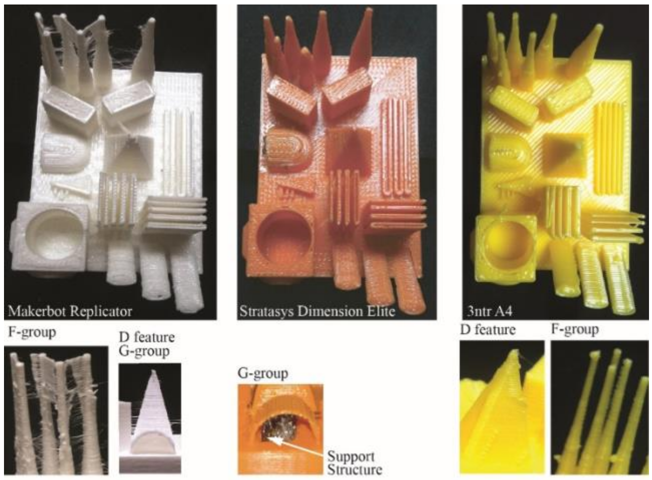
The replicas are evaluated by calculating AQI, according to the rules given in Table 3. Table 5 resumes the achieved score of the three 3D printers for each underlying indicator.

Replicator produced a part with no gaps between adjacent infill lines and thus the machine appears to extrude the right amount of plastic to correctly infill the sections with the largest area (E1, E2, H, and M). On the contrary, overheating effect (OH) and stringing effect (STR) are noticed during the infill of smaller sections (D and F) due to a slow retraction of the filament with respect to the speed at which the extruder jumps from one section to another in the same layer.

Table 4. 3D printing parameters for the fabrication of the replicas.

	Makerbot Replicator	Stratasys Dimension Elite	3ntr A4
Material	PLA	ABS	PLA
Material colour	White	Orange	Yellow
Filament diameter [mm]	1.75	1.75	2.85
Slicer	MakerBot Desktop (Proprietary)	Catalyst Ex (Proprietary)	Kisslicer (Open)
Infill density	100%	Solid (100%)	100%
Nozzle size [mm]	0.40	0.35	0.40
Extrusion Width [mm]	0.40	NA	0.40
Layer thickness [mm]	0.30	0.178	0.30
Nozzle temperature	195°C	NA	195°C
Bed temperature	No heated bed	NA	60°C

Legend: NA – value not available



(a) (b) (c)

Fig. 3. Reference parts produced by means of Makerbot Replicator (a), Stratasys Dimension Elite (b) and 3ntr A4 (c).

Stratasys Dimension Elite achieved the lowest score for the $NOSUP_{bridge}$ because the building of the feature shows the presence of support structures. In fact, the proprietary software of the Stratasys machine does not allow to disable the creation of supports within the build settings. The absence of stringing (STR), overheating (OH), ringing (RIN) and blob (BL) effects demonstrates the high level of industrialization of the Dimension Elite from the point of view of mechanical and control systems. However, the GACI indicator achieved only a medium evaluation because gaps are visible between adjacent lines into the infill area and the number of gaps seems to be a function of the orientation of the features (E_1 and E_2).

3ntr A4 printer reached the lowest score as far as the blob effect (BL) is concerned. This excess of material can be explained by an incorrect flow rate that leads to prime an unnecessary amount of PLA, which is left on the part surface during the stationary retraction of the filament. This conclusion is confirmed by the high score of the STR indicator, because the stringing effect is absent due to the accurate filament retraction.

According to the values of the AQI score, the replica of the reference part with best aesthetic quality was fabricated by the MakerBot Replicator (AQI = 14), whereas the quality

Table 5. Detail of the AQI score for the three compared machines.

Indicator	Makerbot Replicator (white replica)	Stratasys Dimension Elite (orange replica)	3ntr A4 (yellow replica)
OH	1	2	1
GACI	2	1	1
STR	0	2	2
DEL	2	0	2
NOWH	1	1	1
$NOSUP_{bridge}$	2	0	1
$NOSUP_{shell}$	2	1	2
BL	2	2	0
RIN	2	2	2
AQI	14	11	12

of the replicas printed by the other two machines is worst. With an AQI of 12 the 3ntr A4 printer performed slightly better than the Stratasys Dimension Elite, that achieved an AQI of 11.

6. Conclusions

This work presented a preliminary study for the evaluation of the aesthetics quality of 3D printed parts. A reference part was designed with the aim of stressing the limit of the layerwise process by being representative of all typical 3D printing defects. Moreover, a benchmarking methodology was developed to quantitatively evaluate the aesthetic quality of 3D printers through the proposed reference part. Benchmarking results were summarized using a unique indicator named Aesthetic Quality Index (AQI).

The proposed methodology was used for a comparison of three different 3D printers. The MakerBot Replicator was identified as the machine that fabricated the artefact replica with the best aesthetic quality. Beyond this result, since the reference part includes the most common 3D printing defects, it can be used to characterize the machine, but also for the optimization of process parameters.

Further investigation is currently ongoing for extending this study to other 3D printers while increasing the number of testers for the benchmarking procedure. Beside aesthetics, additional underlying pure technical indicators will be considered to account for other quantitative aspects, like the minimum thickness of infill, that affect the quality of 3D printed parts. Finally, the STL model of the artefact can be downloaded for free from the open-source GrabCad library [33], so the described methodology can be easily replicated by the scientific community to extend this research to a wider range of 3D printers.

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