Evaluation of 3D printed mouthpieces for musical instruments

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Abstract

Purpose – The purpose of this study is the evaluation of advantages and criticalities related to the application of addtive manufacturing (AM) to the production of parts for musical instruments. A comparison between traditional manufacturing and AM based on different aspects is carried out.

Design/methodology/approach – A set of mouthpieces produced through different AM techniques has been designed, manufactured and evaluated using an end-user satisfaction-oriented approach. A musician has been tasked to play the same classical music piece with different mouthpieces, and the sound has been recorded in a recording studio. The mouthpiece and sound characteristics have been evaluated in a structured methodology.

Findings – The quality of the sound and comfort of 3D printed mouthpieces can be similar to the traditional ones provided that an accurate design and proper materials and technologies are adopted. When personalization and economic issues are considered, AM is superior to mouthpieces produced by traditional techniques.

Research limitations/implications – In this research, a mouthpiece for trombone has been investigated. However, a wider analysis where several musical instruments and related parts are evaluated could provide more data.

Practical implications – The production of mouthpieces with AM techniques is suggested owing to the advantages which can be tackled in terms of customization, manufacturing cost and time reduction.

Originality/value – This research is carried out using a multidisciplinary approach where several data have been considered to evaluate the end user satisfaction of 3D printed mouthpieces.

Keywords Fused deposition modelling, Additive manufacturing, Stereolithography, Musical instruments, Dental materials

Paper type Research paper

Introduction

Additive manufacturing (AM) can be defined as the set of technologies allowing the manufacturing of a component from a CAD model in short time. Different materials and technologies can be adopted to build products through AM techniques (Gibson *et al.*, 2010). Each manufacturing technology presents peculiarities, advantages and limitations, as discussed in Pham and Gault (1998), but the description of each single technology is behind the scope of this work. Just to provide the reader with an example, the fused deposition modelling (FDM) is one of the most popular techniques because of its low costs and wide range of available materials (Agarwala *et al.*, 1996; Pandey *et al.*, 2003). FDM is based on the melting of a wire in ABS or PLA plastics in a nozzle along paths generated from the slicing of a CAD 3D model. It holds the largest market share and many research results are available in literature, making it a well-known manufacturing process. However, it is important to underline some FDM limitations such as low layer resolution, rough surface, component anisotropy, low strength, stairs effect and so on. A completely different approach is used in other AM techniques, such as selective laser sintering (SLS) (Beaman and Deckard, 1986) and stereolithography (SLA) (Cooper, 2001): a high energy source, namely, a laser or UV light, is used to solidify the primary material (metal or plastic powders for SLS; a liquid resin for SLA) to obtain the final shape with high accuracy, resolution and low roughness (Di Angelo *et al.*, 2017). A disadvantage of the SLA technique is the time degradation – the material changes its properties and shape in time. However, this drawback can be mitigated through post-processing curing with heat and UV rays. On the other hand, SLS produces durable parts melting metal powders with good mechanical properties, but with a higher cost, both for raw material and machine. Nowadays, AM techniques are used to produce small series components, aesthetical prototypes, customized products for evaluation and parts in wax to allow casting. Focussing the attention on the development of musical instruments, AM can be useful in two main applications – reconstruction and replication of ancient musical instruments for conservation reasons and design of musical instruments

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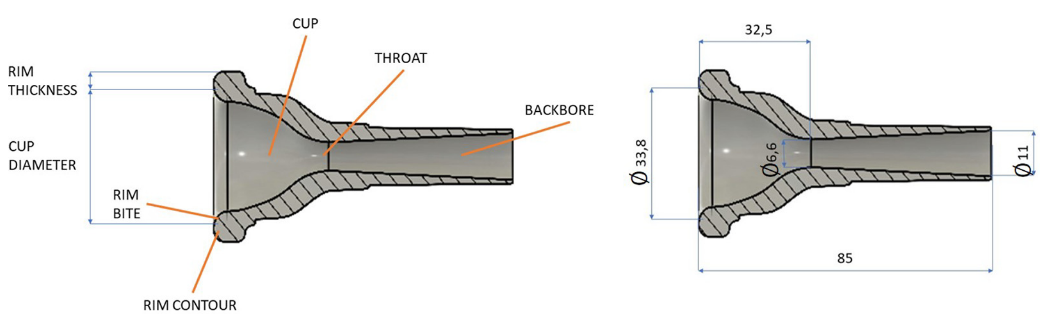
with specific features not achievable through traditional manufacturing. About the first application, ancient musical instrument components (i.e. wooden mouthpieces) are very rare, sensitive and susceptible to damages; moreover, fires, earthquakes, flooding or robbery can lead to the loss of rare musical instruments. Technological instruments such as X-ray tomography scans can be used to reconstruct the 3D shape. When the 3D model is obtained, AM technologies can be used to manufacture the parts. Broadly speaking, the quality of the AM musical instruments is affected by the layer thickness and machine accuracy used to manufacture it. Celentano *et al.* (2016) show that the surface roughness (with ABS plastic) which can be obtained through FDM can lead to air leakages and imperfections at the surface level, making the part not suitable for the musician because of the low comfort. On the other hand, SLS and SLA allow better surface finishing creating smoother and more comfortable parts without problems of air leakage. Sources available in literature (Zoran, 2011) also suggest the use of Polyjet technology for the musical instrument manufacturing: the multi-materials capability assuring good accuracy and surface smoothness are strength point. The multi-material printing capability has been used to manufacture a flute with soft and rigid regions, particularly interesting in the valve areas, used to change air pressure inside the channels. In this way, different pitches are obtained, so that the human perception of a sound wave at a specific frequency is guaranteed. However, as it happens for SLA, Polyjet suffers from the material decomposition in time, making it useful for prototype manufacturing. It is worth nothing that AM materials and building processes affect the obtainable sound because of different properties such as density, accuracy, heat resistance, strength, roughness and porosity. The ancient instrument reconstruction is described in Savan and Simian (2014), where an ancient cornett is CT-scanned and a subsequent manufacturing using nylon with SLS technology is described. The research of new shapes useful to obtain extreme acoustic capabilities is described in Kantaros and Diegel (2018) where a discussion of the AM techniques that can be used is presented. Following Zoran and Maes (2008), musical instruments must be stiff and strong to avoid deformation that can affect the sound and the acoustic requirements.

Regarding wind instruments, additional constrains must be considered: the air flowing inside the instrument creates moisture that can change the characteristics of the sound; in addition, the material used to produce the mouthpiece, or in general the components close or in contact with the mouth, must be biocompatible. Nevertheless, AM has a great potential to support wind musical instruments, because complex shapes can produce unexplored and unconventional sounds, showing customization potentials as well (Dabin *et al.*, 2016). As a matter of fact, complex geometries can be manufactured only by additively processes and not by removal or moulding techniques, since AM does not show limitations in geometry and manufacturing constraints (Aita-Holmes *et al.*, 2015). The lack of design contraints perfectly fits the high customization needed in the musical instrument design process thanks to the employment of AM techniques. Indeed, the design process can be faster, easier to produce, cheaper, and more end-user appealing, well described by the musician-tailored design concept (Lorenzoni *et al.*, 2013).

Table I Requirements relative importance

	Quality of sound	Customization and personal symbol	No gluing lips when cold	Mouth and lips comfort	Buying cost	Mouthpiece easiness of storing	Loudness of sound	Sum of line values	Relative importance
Quality of sound	1	2	2	1	2	2	2	12	24.5
Customization and personal symbol	0	1	0	0	1	2	0	4	8.2
No gluing lips when cold	0	2	1	1	1	2	1	8	16.3
Mouth and lips comfort	1	2	1	1	2	2	1	10	20.4
Buying cost	0	1	1	0	1	2	0	5	10.2
Mouthpiece easiness of storing	0	0	0	0	0	1	0	1	2.0
Loudness of sound	0	2	1	1	2	2	1	9	18.4
Sum of numbers in the sum of line values rows								49	

Figure 1 (a) Mouthpiece geometry and design parameters; (b) commercial mouthpiece dimensions [mm]



(a) (b)

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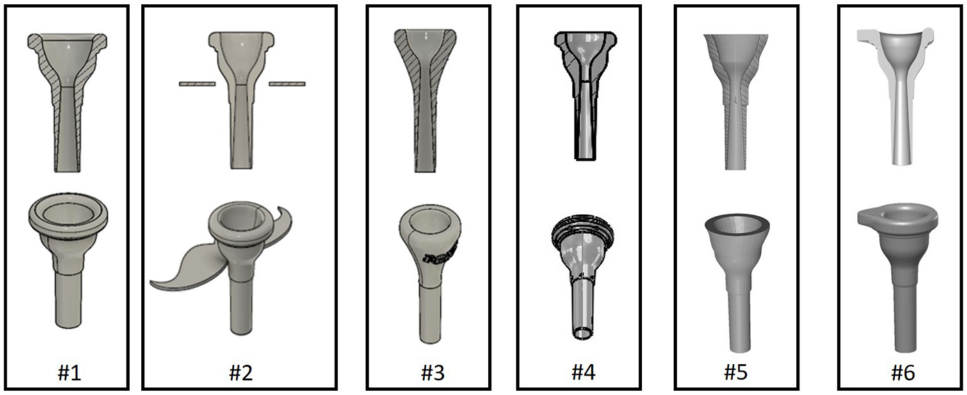
Figure 2 Manufactured mouthpieces geometries



The aim of the study is the evaluation of the AM technology as a potential way to produce musical instruments parts: its novelty and originality lie in the development of a methodology useful to evaluate purposes. The limits of current literature are that available papers describe how it is possible to produce parts obtained through AM, but the description of procedures to follow to score alternatives, based on the end user satisfaction, is not described.

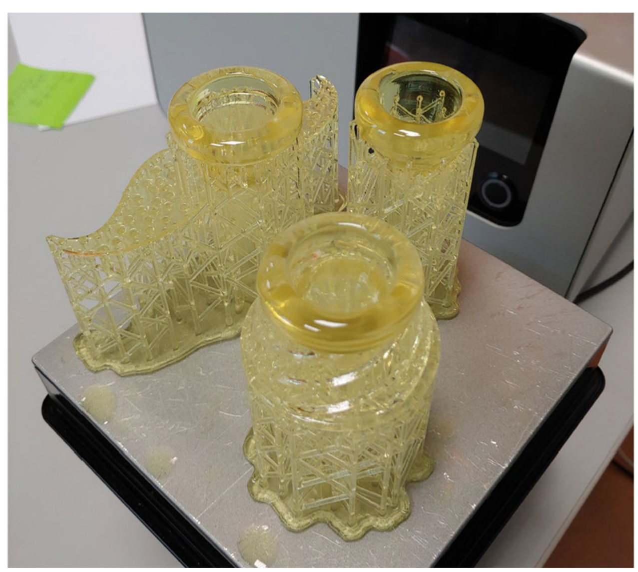
This work is organized as follows. After this section, the mouthpiece for trombone product is analysed keeping into consideration the requirements by the end-user. In the next section, the design of mouthpiece parts is described, together with some notes on possible materials and technology which can be used. Finally, another section describes the tests carried out to evaluate the end user satisfaction of different kinds of mouthpieces; the conclusion ends the paper.

End user-oriented approach

Modern engineering aims to customer satisfaction: methodologies, such as quality function deployment (QFD), Taguchi, robust design (Frizziero *et al.*, 2019), are fundamental to drive the design towards products that are perceived with high value by the end user (Ulman, 2017). This approach has been followed in this study, following these phases: interview with end users, main requirements detection, and ranking of requirements importance. In the following, several design alternatives have been proposed and evaluated through a multi-attribute decision-making analysis (MADM) approach, used to score the solutions based on the end users' feedbacks. At first, a set of interviews has been carried out involving a professional practitioner of trombone and two different professors of music: the needs suggested by users have been regrouped where similar concepts were expressed. A matrix has been used to compute the relative importance of each requirement. All the requirements are written in rows and columns, and a value is filled in the intersection cells (Table I): 1 if the requirement in rows has the same importance of the requirement in column, 2 if the requirement in rows is more important than that in columns, 0 otherwise. At the end of each single line, the sum of numbers is computed, and the overall sum of these sums is

Figure 3 Original (brass) and manufactured mouthpieces in AM: the orange ones in SLA while the white ones by FDM technology

Figure 4 Mouthpiece growing direction to avoid material support in the interior channels



recorded at the bottom of the table. The relative importance of each requirement can be computed by dividing the sum value of the line by the overall sum.

Mouthpiece design

This section mainly focusses on the mouthpiece geometry description, alternative designs and manufacturing technology. From the literature (Svoboda and Roth, 2017), there are two different techniques to play a trombone – the downstream (the more common) and the upstream. The difference comprises the dominant (wider vibrations) lip and in the direction of the exiting air flow from the mouth (respectively towards down in the downstream and up for the upstream). This air flow impacts the inner part of the mouthpiece, flows through the mouthpiece throat section and goes into the instrument itself. The produced sound strongly depends on the mouthpiece geometry: there are different geometry parameters that affect the sound such as cup, rim, throat and backbore dimensions (Figure 1(a)).

The shape of a commercial metallic (brass) mouthpiece, whose original dimensions are reported in Figure 1(b), has been replicated in AM using SLA and FDM techniques to evaluate the effect of the change in material. A set of different mouthpiece geometries has been 3D modelled and manufactured to investigate the influence of the geometry changes on the sound.

Alternative mouthpiece geometries

The first mouthpiece, referred in the following of the text as #1, has the same shape of the commercial metallic mouthpiece (#7) used by the musician involved in tests. To satisfy player needs in terms of external personalization and improved component comfort, the first mouthpiece alternative version, called #2, is personalized with moustache in the exterior part and with a lower value for the inner rim radius to make the mouthpiece more comfortable for the player with respect to the original one (1.72mm with respect 3.75mm of #7) (Figure 2). The #3 mouthpiece is designed for light music purposes, with a smaller cup volume owing to a reduction of diameter (29.4 vs 33.8mm) and depth (25.1 vs 32.5mm). In the exterior, a minimal design is adopted with a writing personalization. Figure 2 shows a design alternative (#4) with the same internal shape as the previous model but with a more traditional external shape. Afterwards, two completely different alternatives from a geometry perspective are designed; the first one (#5) is based on a non-axisymmetric shape, with almost sharp edges of the rim and an elliptical cup, with axis length of

Figure 5 Recording studio

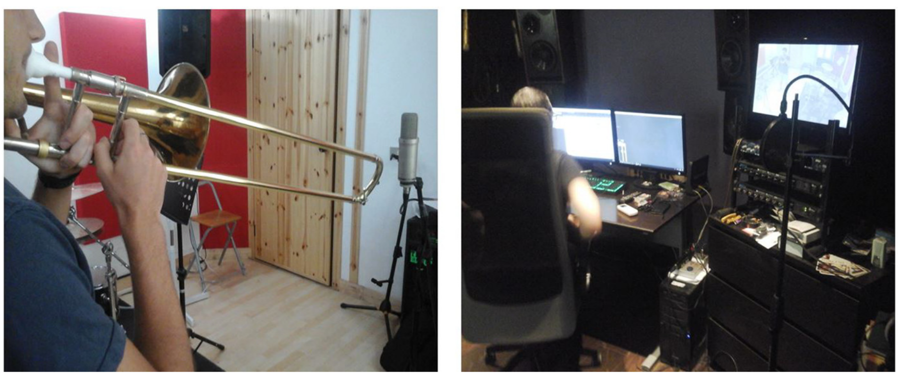


Figure 6 Sound quality assessment by experts

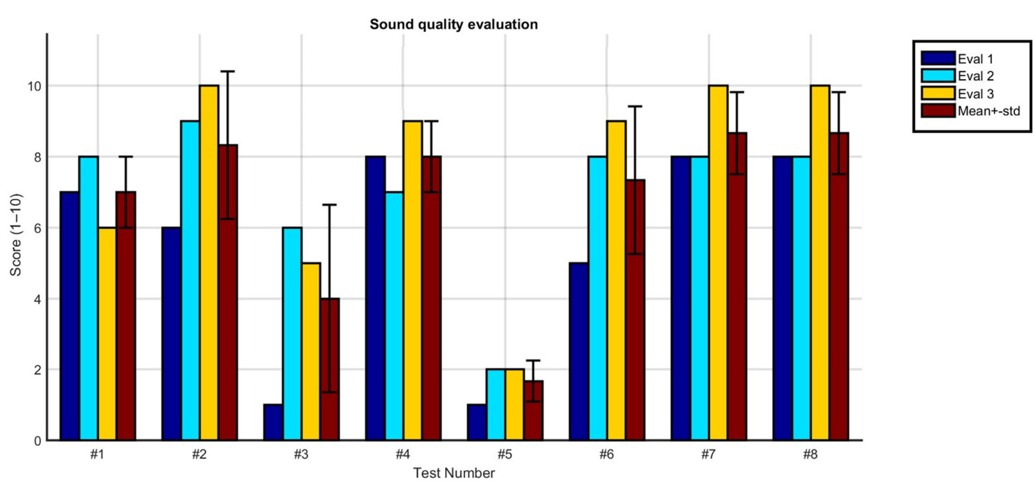


Figure 7 Mouthpiece comfort assessment by musician

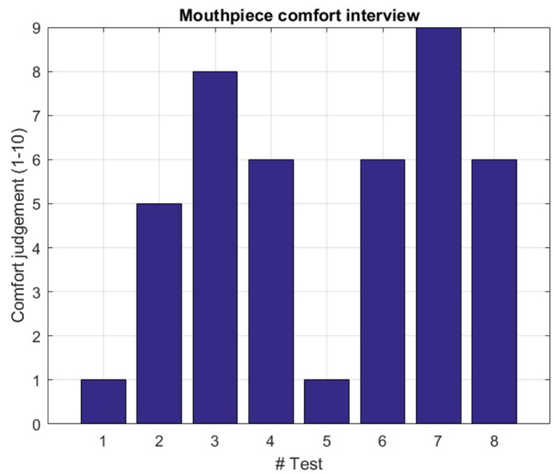
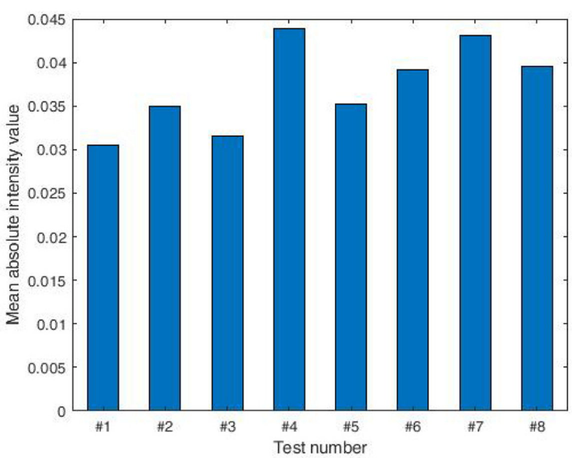


Figure 8 Mouthpiece sound analysis assessment in terms of mean absolute intensity value



23.9 and 30.1mm. The second one (#6) follows the original shape, but a small bulge is added to increase the player's comfort and to reduce the lip swelling in case of long period of playing. The metallic mouthpiece usually played by the musician involved in the test has been labelled with #7; finally, the specimen #8 is identical to #4, apart from the reduction of the dimensions of the mouthpiece support structure which is removed after the printing.

Additive manufacturing technology and material

To produce the above mouthpiece models, SLA technique is chosen in specimens #2, #3, #4, #5, #6 and #8 because of the external high-quality finishing, the overall accuracy level that is possible to achieve and its quite affordable prices. The smooth surface characteristic is extremely important not only for exterior design, but also for player's comfort and sound creation: the Formlabs Form 2 machine has been used. One of the problems related to the SLA technology is that the material support is made of the same final object material and cannot be removed by washing procedures but only by hand. For this reason, the placement of the material support must be carefully chosen, to have the best geometry where the painstakingly operation of supports removing and following polishing is reduced as much as possible. Specimens #4 and #8 differ only for the design of supports. In #4, a support density of 1.30 and a support-part contact dimension of 0.4mm is chosen in the pre-processing software, while in #8, the settings are 1.00 and 0.9mm. These setting modifications do not affect the sound performances but contribute only at the external surface finishing. One of the models (#1) is manufactured using an FDM Creality 3D CR 10s5 machine to compare the geometry and sound characteristics and to check the impact of the FDM criticalities listed in literature (Figure 3); the metal used in high quality commercial mouthpieces (#7) is brass.

The mouthpiece internal channel needs to be smooth to produce a good sound, so that no material support must be placed inside. For this reason, the only possible object orientation is to place the backbore axis perpendicular to the building platform and the cup on the opposite side with respect to the building platform (Figure 4). This is the only constraint noticed by the authors while manufacturing the alternative mouthpiece geometries.

The Form 2 SLA machine can use different types of photoreactive resins, each one assuring good exterior smooth surface. In this project, a biocompatible resin (Dental SG) that is usually used for dental prosthesis or for objects in direct contact with human tissues has been selected; in this way, the possibility of contact between toxic materials and player mouth is avoided. To overcome the material degradation in time, a post-processing method, based on UV ray curing, is used to strengthen the mouthpieces and to avoid possible deformations during the experimental tests. It is worth noting that after the post-processing, the mouthpieces change their colour from yellow (Figure 4) to orange (Figure 3).

Test and feedback

All the configurations previously presented have been tested by a single musician and evaluated, respect to the requirements selected after the interviews with end users. In the following paragraphs, the methodology used to evaluate the mouthpiece sound performances, based on the most significant features, is described.

Quality sound, loudness and comfort

The comfort and quality sound have been assessed by asking to a musician to play the same music piece with eight mouthpieces. The musician is asked to score the mouthpieces from 1 (low comfort) to 10 (high comfort). The recordings have been acquired using a professional Rode NTK microphone and a Motu 8pre USB amplifier system, with a 44100Kh frequency, and saved in WAV format (Figure 5). About sound quality, two Professors of music and the musician himself have been asked to listen to the high-quality registrations of the piece played with the eight mouthpieces. All the experimenters are unaware that #4 and #8 are identical; this is done to check repeatability of judgement.

The following Figure 6 shows the results of three scorings (musician and two Professors) and the mean and standard deviation. A good agreement can be noticed between experts scoring.

About comfort, the musician keeps into consideration features such as lips adhesion, roundness of the mouthpiece, air leaks from sides and surface roughness. The scores given in the eight tests are summarized in Figure 7.

The sound loudness is a key parameter in the evaluation of wind musical instruments. The mean intensity value of the sounds in tests can be a good reference for non-expert people in the music field: the higher the sound intensity, the better the sound perception. A sound analysis in time domain and a comparison of the mean intensity value have been carried out, and the mean absolute value of the sound intensity (where all the sound pauses are deleted) is included in Figure 8.

As the reader can notice, quite reduced differences can be noticed among all the mean intensity values. The mouthpieces #4, #6 and #8 show performances like the metallic one (#7). The lowest sound quality is achieved by the FDM mouthpiece because of air leaks. Scores are given assuming 1 for null intensity value and 10 for the highest intensity.

Economical assessment

A comparison between mouthpieces has been carried out keeping into account economic issues, with all the prices referring to June 2019. The commercial cost (€200) has been considered for the brass mouthpiece. When dealing with mouthpieces produced by AM techniques, direct material cost, machine depreciation, VAT, 50 per cent reseller/producer gain have been considered to assess costs (Table II). The Form 2 machine costs roughly €4,000, while the FDM machine costs less than €1,000. For all the machines, a pay-back time of 3,000 h (average 4 months of continuous printing) has been considered. About the cost of raw materials, a litre cartridge of dental resin costs €250, while a coil of PLA wire (1 kg) can be purchased for €25.

Other assessments

The metal mouthpiece can lead to the gluing of lips when playing trombone outside in cold winter days, and a score 3 is given because it must be stored in a pocket to keep it warm. On the other hand, both FDM and SLA score 10 because both PLA and resins are insensitive to low temperatures. About customization, FDM and SLA outclass metal traditional mouthpieces because it is possible to add writings or distinctive features (such as a pair of printed moustache asked by a musician).A higher score in customization and personal symbol requirement is given to SLA with respect to FDM because it is possible to model small details and thin surfaces without the risk of collapsing. Only one mouthpiece has been manufactured through FDM because the roughness is a main factor at play which reduces the appealing of this technology. It is worth nothing that FDM technology suffers from high roughness values because of two main factors – filament profile and staircase effect – which are visible even to a naked eye (Di Angelo *et al.*, 2017). Some experimental measurements were performed using the *Alpa Face Test25* roughness tester (Figure 9) in the region near the contact area with the mouth. The results in terms of R_a are collected in Table III. As it can be seen, the FDM technology is affected by a surface roughness that is an order of magnitude higher than SLA technology, and the overall comfort can be compromised. About mouthpiece easiness of storing, the overall dimensions of the mouthpiece have been considered.

Table II Costs assessment

Mouthpiece #	Resin/wire quantity	Time to print	Direct/indirect costs	Reseller/producer gain added	Total price [€] (incl. VAT 22%)	Score
1	13 g	1h 35 min	0.85	1.28	2	10
2	50.81 ml	6h 45 min	21.70	32.55	40	8
3	32.49 ml	6h 5 min	16.23	24.35	30	9
4	38 ml	5h 45 min	17.17	25.75	31	9
5	27.50 ml	5h 45 min	14.54	21.81	27	9
6	34.09 ml	6h 5 min	16.63	24.95	30	9
7	/	/	/	/	200	1
8	38 ml	5h 45 min	17.17	25.75	31	9

Figure 9 Roughness measurements for mouthpiece produce using SLA and FDM technology

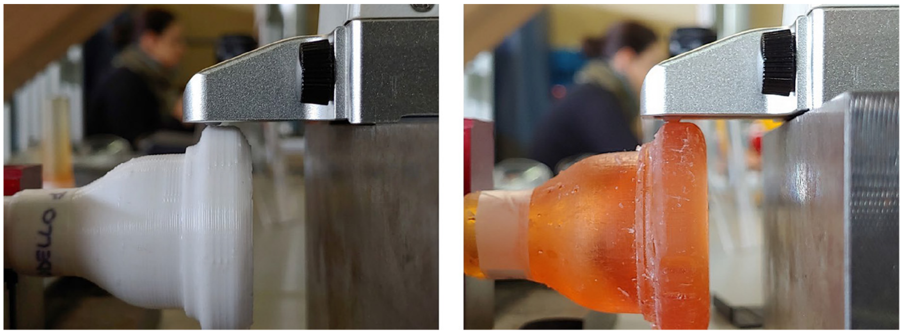


Table III Roughness measurements

AM technology	Mean value (μm)	SD
SLA	3.29	0.70
FDM	24.99	1.96

Multi-attribute decision-making analysis

A MADM analysis has been carried out to understand the mouthpiece better fitting the end-user needs: The technique for order preference by similarity to ideal solution (TOPSIS) (Ishizaka and Nemery, 2013) approach has been followed (Ceruti *et al.*, 2018). At first, a table listing all the requirements, their relative importance and the scores for each single solution is filled: the last column lists the sum of the square of the values in the same line (Table IV).

In the following, the matrix is normalized by dividing the scores times the sum of squares of the line and multiplying by the relative importance of the requirement (Table V). The best and worst value in each line is recorded. The Euclidean distance of each solution from the best (D_{best}) and worst (D_{best}) solution is found. Finally, the relative distance of each single configuration from the worst solution can be computed by Ishizaka and Nemery (2013):

$$S = \frac{D_{worst}}{D_{worst} + D_{wbest}}$$

The higher is the distance between the solution and the worst configuration, the better it is. From this analysis, it appears that the most end-user satisfying solution is the mouthpiece #8, which is even superior to mouthpiece #7 in metal.

The application of the methodology based on QFD and TOPSIS was fundamental to consider in a proper way pros and cons of all the design alternatives proposed. The application of a design process like the one described in this work, where different products are evaluated in a multi-disciplinary way, keeps into consideration several requirements (each one with a relative weight and importance) and provides more reliable results than a subjective evaluation carried out by musicians.

Conclusion

The scope of this paper is the evaluation of AM technologies in the production of parts of musical instruments. A QFD approach has been applied to detect what the end user wants; a set of alternatives has been designed and produced with FDM and SLA AM techniques. Finally, the compliance of the design alternatives to the single end-user requirements has been scored, and a TOPSIS approach has been applied to solve this multi-attribute decision problem. The methodology has been applied to a mouthpiece for trombone. When a comparison is carried out between traditional metallic mouthpieces and the ones produced with FDM and SLA techniques, analyses show that the best design solution is obtained with a SLA-printed mouthpiece. AM provides high customization capability and good economic impact for low production series. With an accurate design and material selection, similar sound to commercial mouthpieces can be obtained using SLA technology. The porous structure typical of FDM components does not assure good sound quality in the tests carried out.

The conclusion that can be drawn from this study is that AM can be applied to increase end-user satisfaction of musical instruments parts. Further studies involving different musical

Table IV TOPSIS matrix

Requirement	Relative importance	#1	#2	#3	#4	#5	#6	#7	#8	Sum of squares in line
Quality of sound	24.49	7	8.2	4	8	1.7	7.3	8.7	8.7	403.8
Customization and personal symbol	6.12	4	10	4	4	4	4	1	4	197
No gluing lips when cold	18.37	10	10	10	10	10	10	3	10	709
Mouth and lips comfort	20.41	1	5	8	6	1	6	9	6	280
Buying cost	10.20	10	8	9	9	9	9	1	9	570
Mouthpiece easiness of storing	2.04	10	5	10	10	9	8	10	10	670
Loudness of sound	18.37	6.8	8	7	10	8	9.1	9.8	9.1	584.9

Table V TOPSIS normalized matrix

Weighted matrix	#1	#2	#3	#4	#5	#6	#7	#8	Best	Worst
Quality of sound	0.4245	0.4973	0.2426	0.4852	0.1031	0.4427	0.5276	0.5276	0.5276	0.1031
Customization and personal symbol	0.1243	0.3108	0.1243	0.1243	0.1243	0.1243	0.0311	0.1243	0.3108	0.0311
No gluing lips when cold	0.2591	0.2591	0.2591	0.2591	0.2591	0.2591	0.0777	0.2591	0.2591	0.0777
Mouth and lips comfort	0.0729	0.3644	0.5831	0.4373	0.0729	0.4373	0.6560	0.4373	0.6560	0.0729
Buying cost	0.1790	0.1432	0.1611	0.1611	0.1611	0.1611	0.0179	0.1611	0.1790	0.0179
Mouthpiece easiness of storing	0.0305	0.0152	0.0305	0.0305	0.0274	0.0244	0.0305	0.0305	0.0305	0.0152
Loudness of sound	0.2135	0.2512	0.2198	0.3140	0.2512	0.2858	0.3077	0.2858	0.3140	0.2135
D_best	0.629	0.302	0.361	0.291	0.748	0.302	0.370	0.289		
D_worst	0.414	0.607	0.585	0.593	0.252	0.562	0.728	0.617		
(S) Relative distance from worst	0.397	0.668	0.618	0.671	0.252	0.651	0.663	0.681		

instruments and parts should be carried out to investigate other design scenarios. An industrial production of 3D printed mouthpieces is suggested to companies.

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