Progress in Additive Manufacturing
https://doi.org/10.1007/s40964-021-00183-5

FULL RESEARCH ARTICLE

A design of experiment approach to 3D-printed mouthpieces sound analysis

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Received: 26 June 2020 / Accepted: 10 April 2021

Abstract
Nowadays additive manufacturing is affected by a rapid expansion of possible applications. It is defined as a set of technologies that allow the production of components from 3D digital models in a short time by adding material layer by layer. It shows enormous potential to support wind musical instruments manufacturing because the design of complex shapes could produce unexplored and unconventional sounds, together with external customization capabilities. The change in the production process, material and shape could affect the resulting sound. This work aims to compare the music performances of 3D-printed trombone mouthpieces using both Fused Deposition Modelling and Stereolithography techniques, compared to the commercial brass one. The quantitative comparison is made applying a Design of Experiment methodology, to detect the main additive manufacturing parameters that affect the sound quality. Digital audio processing techniques, such as spectral analysis, cross-correlation and psychoacoustic analysis in terms of loudness, roughness and fluctuation strength have been applied to evaluate sounds. The methodology herein applied could be used as a standard for future studies on additively manufactured musical instruments.

Keywords Additive manufacturing · Sound analysis · Musical instruments · Design of experiment · Stereolithography

1 Introduction

Nowadays, AM is used to produce prototypes, mostly for validation tests instead of taking advantage of its incredible design freedom capability [1]. Nevertheless, AM is becoming to be used also in the musical field for final product generation due to two main reasons: (1) reconstruction and replication of ancient musical instruments for conservation reasons [2]; (2) design with optimization of new musical instruments for innovative shape research to produce the desired sounds [3].

There is an increasing interest in the research community about these topics. As an example, the 3D model of an ancient instrument is reconstructed by Computed Tomography (CT) scans and subsequently manufactured using AM technology [4], for example, employing nylon with Selective Laser Sintering (SLS) technology [2]. Musical instrument reconstruction can be motivated by a thirst for knowledge and understanding of ancient instruments for historical conservation reasons. Ancient musical instrument components (i.e. wooden mouthpieces) are very rare, sensitive and susceptible to damages. For that reason, it is important to replicate their 3D models using powerful technological instruments as X-ray tomography and CT scans and then use the models to manufacture a faithful copy in an easy way using, for instance, AM. Sometimes, ancient musical instrument parts can be either recreated from manufacturers' technical drawings instead of 3D reconstructed models, as described in [5]. Several AM techniques (FDM, polyjet, Digital Light Processing and Digital Light Synthesis) are used to reach satisfactory accuracy.

On the other hand, the research of innovative shapes useful to obtain unexplored acoustic capabilities is described in [3] with a discussion of the AM techniques which can be used. Indeed, AM gives the possibility to customize the musical instrument according to the musician's needs, producing innovative shapes that are optimized iteratively, thanks to musician feedbacks together with sound analysis in a fast design-to-manufacturing cycle by the Digital Manufacturing concept employment [6]. As an example, [7] describes the design of an end-user-oriented component that

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is manufactured in AM to create an efficient clarinet mouthpiece customized for a bell's palsy patient. A musician-tailored design approach is used to design and manufacture saxophone mouthpiece according to players' needs [8].

To design new shapes to be able to produce unexplored acoustics, the musical instrument design must consider several key factors. The strength and stiffness of musical instruments must be guaranteed to avoid deformation which reflects on sound modifications. Furthermore, in the case of wind instruments, additional constraints must be taken into mind. Designers must consider the moisture that can be produced when the air flows inside the instrument and the material, that must be biocompatible, used to produce the mouthpiece because the component is close or in contact with the mouth [3].

Looking at the available researches about new design frontiers in musical instruments, [9] describes the digital optimization of an acoustic guitar using technological tools leading to the uniqueness of the acoustic sound that is created. Indeed, players can customize their sounds and their acoustic guitar substituting the large chamber with different small ones. [10] describes the design and manufacture of a flute with soft and rigid regions, using AM. Polyjet technology [11] has been selected to manufacture different parts made by different materials. The multi-material capability is employed in the valve areas and exploited to change the air pressure inside the channels to get different pitches (namely the human perception of a sound that allows the ordering on a frequency-related scale [12]).

From this brief introduction, it can be noticed that AM has great possibilities with wind musical instruments: complex shapes could produce unexplored and unconventional sounds; the customization allows adding personal symbols and comfortable shapes for the single individual; biomaterials can be used [13]; problems related to lip freezing in winter could be avoided using plastics instead of metals. Using AM technologies instead of traditional manufacturing processes, designers can exploit the advantages of additive technology. This is especially true for small batches of production, as it happens in custom musical instruments design. Acknowledged advantages of AM are the absence of manufacturing constraints, no shape limitation which perfectly fit the high customization, opening new frontiers in the musical instrument design process. Several contributions in the literature focus on the design and manufacturing of woodwind mouthpieces for saxophone or clarinet [4, 5, 8, 14]. The source [15] focuses on the production of brass instruments such as the trombone's mouthpiece through AM. Indeed, this work can be seen as a continuation of the research carried out in [15].

To contribute to the research topic of musical instrument customization and production with AM, this work aims to develop a methodology, not available in literature yet, to compare traditional and additively manufactured music instruments. This methodology could be extended to other kinds of musical instruments. The scope of this paper is to apply a design methodology usually used in an industrial engineering context to a highly customized field represented by the production of musical instruments. In particular, additive manufacturing has been evaluated as a potential candidate for the manufacturing of musical instruments due to the superior design flexibility and customization capabilities assured. An approach based on the Design of Experiment (DOE) methodology and sound quality check in terms of conventional and psychoacoustic analysis has been followed. As a case study, different trombone mouthpieces produced with SLA and FDM additive manufacturing techniques have been investigated to demonstrate that it is possible to obtain almost comparable sound performances compared to commercial metallic components and to search which additively manufactured piece has better sound performances compared with the brass one.

This work is organized as follows: after this brief introduction of AM technology and some examples found in the research community of its employment in the music sector, Sect. 2 will describe the methodology used to compare different mouthpieces with both DOE and sound analysis tools along with the trombone mouthpiece geometry description and the AM technologies employed to manufacture the trombone components. In Sect. 3, the paper contains the results and discussion on how the sound is recorded and how its quality can be evaluated. Sound analysis in both time and frequency domain are discussed to have a confirmation from a numerical point of view that the conclusions drawn are consistent. Section 4 highlights some conclusions and future developments.

This article suggests a methodology useful to evaluate the influence of design parameters of musical instrument's parts—such as material and cup geometry—on the sound performances. This approach has been applied and tested using a case study where a trombone mouthpiece built through additive manufacturing techniques has been analysed.

2 Methodology for performance comparison of instrumental components made in additive manufacturing

The proposed methodology is based on the following procedure. At first, a professional musician plays a short musical track with different mouthpieces, having different characteristics, in a professional recording room. The recorded tracks are then evaluated by different experts in classical music and a score is given for each mouthpiece depending on their impressions. In the following, a mathematical analysis is carried out to understand how each design characteristic affects the produced sound: this is carried out based on an objective data analysis procedure relying on factorial analysis using the Design of Experiment (DOE) methodology [16]. Moreover, the recorded tracks are analysed with some mathematical tools [17], such as Fast Fourier Transform, Cross-correlation function, and Spectrogram, to check a correlation between the results of the DOE analysis and music tracks. Psychoacoustic parameters, like loudness, roughness and sharpness are evaluated to distinguish features of music acoustics too [18]. All the previously cited mathematical tools are described in more details in the following for a better understanding of the methodology. The overall methodology phases are depicted in the flow chart included in Fig. 1.

2.1 Design of experiment methodology

The design of experiment methodology can be defined as a statistically rigorous approach developed to assess the influence of some parameters (called factors) which have some values inside a range (called level) affecting the output of a certain process. DOE helps the understanding of a process and suggests how the factors may affect it. The DOE statistical analysis is based on the comparison of some design input of an experiment, aiming to improve the process knowledge by as few as possible runs, thus reducing the need for numerous tests which may be expensive both in terms of time and costs.

This methodology is used to find cause-and-effect relationships to optimize the output (y_i), by knowing the process inputs ($x_1, x_2, x_{3,\ldots} x_i$) and their interactions (see Fig. 2).

Thanks to the DOE approach, production and design costs can be easily reduced, by reducing the process variance and increasing its understanding. There are different types of DOE analysis, such as full factorial, where all the factors and levels are considered and fractional factorial, where the analysis considers only some of all the possible combinations of factors and levels.

The more common DOE analysis is called 2^k-factorial design, where all the k factors have only two levels and all the possible combinations are 2^k. Without the DOE methodology application, it could be possible to understand, with a trial and error approach, the contribution of each factor to the output. However, in this latter case, it would be hardly understandable the interaction effect among the factors. In the following, a 2^k-factorial design approach will be used to investigate the influence of material and cup dimensions ($k=2$) of a trombone mouthpiece on the sound quality. In this research, the results of the DOE analysis are computed exploiting the capabilities of the Minitab™ software.

2.2 Sound and psychoacoustic analysis tools

To analyse the produced sound from a musical instrument, it is common to examine the recorded data in the time and frequency domain. Usually, the sound amplitude envelop is at first plotted in time to visualize how the sound amplitude changes along the span of the recorded track. The sound amplitude represents the maximum displacement from the equilibrium point of the air particles when the sound wave travels through the air itself. An increase of the sound amplitude means an increase of the force applied to the human eardrum and it grows the perception of the sound intensity. The cross-correlation MATLAB function *xcorr* can be a good tool in the time domain to compare the sound. Thanks to this tool it is possible to measure the similarity of a signal as a function of the temporal translation: this function has been applied in this work on music tracks to capture possible similarities in time of the sound behaviour of different mouthpieces.

To transform the sound amplitude envelop in time to the frequency domain. It is possible to apply a mathematical operation called Discrete Fourier Transform (DFT). Thanks

Fig. 1 Applied methodology for objective comparison of additively manufactured trombone mouthpieces

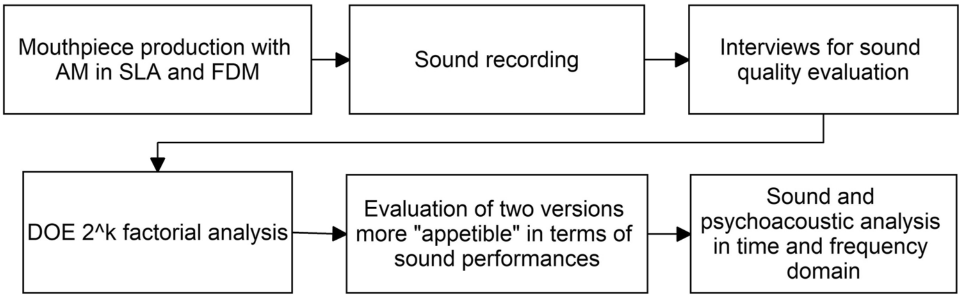


Fig. 2 Simplified process model in the absence of external disturbances

to this function, the sound is digitalized when stored in a computer by a sampling procedure, returning a vector that contains sound intensity values for each frequency f_n, once a given sampling frequency f_s [19] is set by the experimenter.

This mathematical tool allows extrapolating individual frequency components of a given signal in time [20]. Analysis in the frequency domain is preferred compared to the time domain because parameters, as pitch and sound brightness, necessary for sound analysis, are easier to detect and evaluate in comparison with a sound temporal representation, in which the intensity or amplitude of the sound in time is known.

The Fast Fourier Transform (FFT) speeds up the processing speed of the Fourier Transform [21], by producing an array of complex numbers which is often used to calculate the behaviour of magnitude or power versus frequency to represent it as a 2D graph [14].

However, the FFT is a signal analysis where the temporal dimension of the signal is lost, namely the information content about how the frequency domain changes in time are lost. This is the reason for the wide use in music of the spectrogram, which is a complete temporal mapping of how the frequency domain changes. A spectrogram is obtained as a set of single analysis at regular intervals of a small signal time window. The signal batch involved in the analysis is isolated from the whole signal and multiplied by a bell's function window to avoid that the truncation operation affects the result. The 'windowing procedure' is used to obtain the signal spectrum with higher accuracy. There are different types of window but in the present case study, the default window implemented in MATLAB, that is the Hamming, is used [22]. It is important to underline that the window length choice is crucial and based on a trade-off analysis. A better temporal resolution (small window size) is paid back with a worse frequency resolution: it is worth citing the uncertainty principle stating that it is impossible to evaluate simultaneously with arbitrarily precision both temporal and frequency parameters of a signal. In the case study presented in this paper, the window size was chosen after an iterative process to find a good compromise in terms of temporal and frequency resolution. Once available a single recorded track, a spectrogram analysis is applied to it, using different window lengths inside a certain range. In the following, the spectrograms are visually compared and the interval is narrowed until the spectrogram is satisfactory from a visual point of view; the figures of these spectrograms are not included for brevity. However, the result coming from this study shows that too small or too large window length is detrimental for sound analysis because several details are lost, confirming what expected. This is the reason why a trade-off value has been set for this study.

For this work, according to the literature contribution regarding musical instruments sound analysis [23], authors used the MATLAB function $Y = fft\ (X)$ that computes the discrete Fourier transform (DFT) of an array X using a fast Fourier transform (FFT) algorithm, where X is the sound signal recording of the musical instrument under analysis. The MATLAB *Spectrogram* function is used to evaluate the frequency domain variation in time of the produced sound of all the mouthpiece alternatives.

The spectral centroid, which can be associated with the barycentre of the spectrum [24] is an important parameter in audio signal analysis to characterize the frequency spectrum. In practice, it is often associated with the brightness of a sound which increases as the spectral centroid increases [25]. The spectral centroid can be evaluated with the following equation (Eq. 1):

$$C = \frac{\sum_{k=1}^{N/2} f(k)|A(k)|}{\sum_{k=1}^{N/2} |A(k)|} \tag{1}$$

where N is the total number of the Fast Fourier Transform (FFT) points, $|A(k)|$ is the spectral value corresponding to the k-th bin and $f(k)$ is the frequency at FFT k-th bin [24].

The fundamental frequency [26] of the sound can be considered as another interesting parameter to see if new materials can substitute the commercial metallic (brass mainly) used for wind musical instruments. This characteristic can be evaluated in MATLAB using the *pitch* function. Further information about the implementation of this and similar functions can be found in the MATLAB software user manual [27–29].

To distinguish musical acoustic features, conventional sound signal parameters are not enough. For this reason, additional psychoacoustic parameters are introduced: loudness focuses the attention on the distribution of critical bands and masking properties in the hearing, describing the human perception of sound volume. This parameter is evaluated with the *acousticLoudness* function, according to the Zwicker loudness definition (ISO 532-1) [30]. Sharpness expresses the quality of the sound and it is strongly related to how pleasant an auditor feels with the sound. If there is high-frequency energy in a sound, then the sound will be sharper: this psychoacoustic parameter can be computed with the *acousticSharpness* MATLAB function, according to DIN 45692 and ISO 532-1 [31]. Finally, fluctuation strength and roughness analyse the time structures of the sound signal. On one hand, fluctuation strength indicates the perception of low-frequency modulations that are discernible individually (computed with *acousticFluctuation* function [32]). On the other hand, roughness indicates the rough-sounding perception of stimuli related to modulations at frequencies too high to be discerned separately. This last psychoacoustic parameter is computed using an open-source function [33], based on the Daniel and Weber algorithm [34]. The authors are aware that this parameter list is not exhaustive and other temporal, harmonic spectral and perceptual audio descriptors should be considered for a complete comparative study and timbre estimation: other factors could be investigated in the following studies. It is worth noting that all these evaluation parameters provide a similar ranking for the manufacturing technologies considered in this paper.

The analysis of the produced sound and the effects of multiple musical instruments design parameters, such as geometry, material and AM technique used to manufacture the instrument, can be investigated thanks to these mathematical tools. The classification of the tools used in this paper is shown in Fig. 3.

2.3 Case study: trombone mouthpiece geometry and material

The trombone is a wind instrument belonging to the brass instrument family. There are different types of trombone, such as soprano, alto, tenor, bass, and contrabass. While the other brass family members have valves to change notes, the trombone has a slide mechanism to change the produced note.

From literature [35], the technique to play the trombone consists of lip vibration and in the change of the airflow direction exiting from the mouth. The mouthpiece helps the lips vibration and canalizes the airflow coming from the mouth towards the instrument itself. The flow impacts the inner part of the mouthpiece then flows through its throat section and goes into the instrument itself, which can be compared to a sounding board.

There are several mouthpiece models: some of them help to reach high registers, while others, the lower ones depending on the component geometry. Indeed, the expert musicians know that the produced sound depends also on the geometry of the mouthpiece and there are some geometry parameters stalwartly affecting the sound. Just to mention, cup, rim, throat and backbore dimensions influence the emitted sound. However, in literature, there is no mention of whether AM technology can be used to produce mouthpieces with equivalent performances compared to the traditional in brass.

The comparison which follows involves the commercial metallic (brass) mouthpiece and alternative versions that are additively manufactured using stereolithography (SLA) [36] and Fused Deposition Modelling (FDM) [37] printing strategies. These two different technologies were selected to evaluate the effect of the change in the material due to their suitability to the case study application and investigate how the acoustical characteristics would be affected by material properties [15]. Indeed, the selected AM technologies use economical affordable raw materials (respectively, photo-sensible resins and thermoplastic polymers) and are largely diffused in labs and the hobby field. A large number of practitioners could access these two technologies. On the other hand, AM technologies based on metal powders, such as Selective Laser Melting (SLM) and Electron Beam Melting (EBM), are used only in advanced industrial contexts, and the manufacturing costs could be so high to reduce the interest for this kind of AM technologies for musical instruments. Moreover, the overwhelming majority of experimenters and practitioners can't access metal AM machines for tests and custom realizations. This is the reason why SLA and FDM technologies are selected for this research.

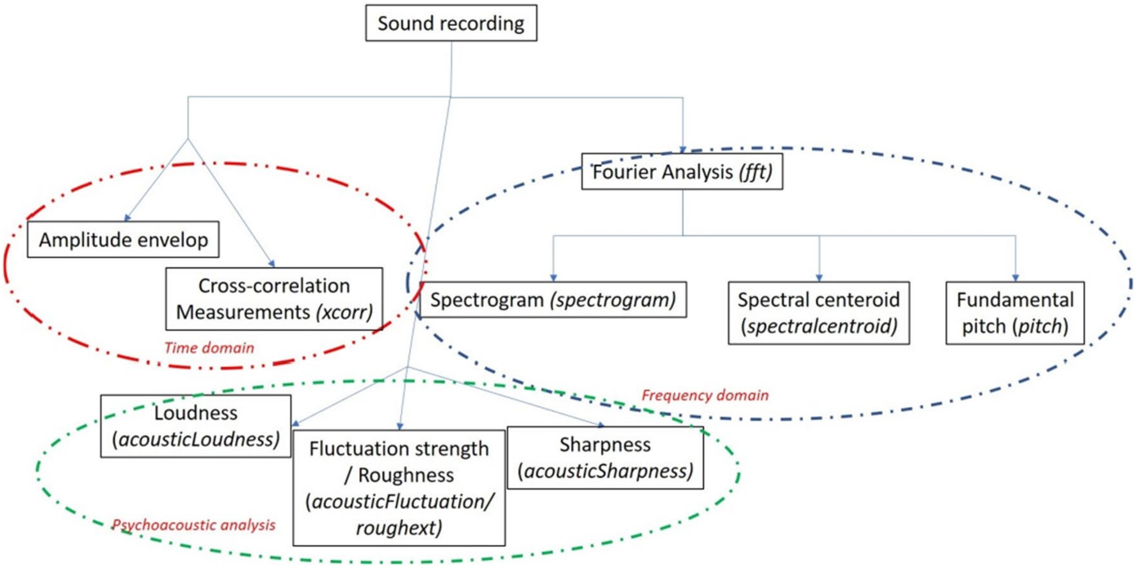


Fig. 3 Applied methodology for sound analysis by the employment of several MATLAB functions (in bracket)

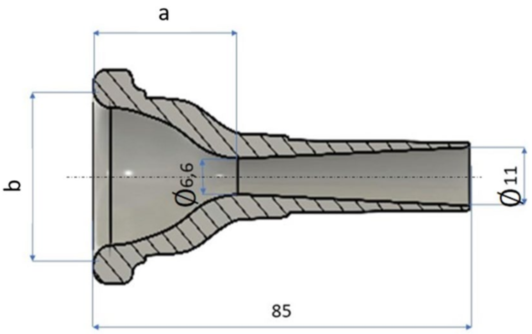


Fig. 4 Technical drawing of the mouthpiece with two variable dimensions affecting the cup volume: **a** cup depth, **b** cup diameter

Fig. 5 Additively manufactured trombone mouthpieces: the SLA version in orange on the left and the FDM one in white on the right

Moreover, the cup dimension has been changed in terms of cup depth (a) and cup diameter (b) in the mouthpiece 3D models, according to Fig. 4. As the last variable, the mouthpieces are manufactured using SLA and FDM to investigate their influence on the sound changes: in this way both material and geometry changes are investigated. All the alternatives were designed according to feedback coming from an expert trombone player, which customized the mouthpiece according to his needs. Two of the manufactured components are represented in Fig. 5.

The rigorous objective analysis that follows, involves the commercial brass mouthpiece (label #1 will be used to refer to it), two versions manufactured in AM using the SLA technique (#2 and #3) and two components made in FDM (#4 and #5). The mouthpiece characteristics are collected in Table 1. According to design requirements, the #3 component was designed with a smaller cup volume (decreased diameter and depth) to fulfil the player needs, namely to have high-pitched and shrill tones. The labels contained in the table will be used in the following as a reference to make the discussion clearer.

Two mouthpiece versions have been manufactured using the SLA technique since an external high-quality finishing can be achieved, together with a smoothness in the inner channel and in the region of mouth contact useful to increase the comfort and reduce the staircase effect. To make the component biocompatible, the Dental SG Resin by Formlabs is chosen. This material is often used for prostheses that are in direct contact with human tissues, to avoid the possibility of contact between toxic materials and the player mouth. For its applications, this resin is studied to be resistant in a moist environment as the mouth still maintaining high stiffness and rigidity. The SLA machine used for this study is Form 2 by Formlabs which allows a layer thickness of 25 ÷ 300 micron.

On the other hand, the other two mouthpiece kinds have been manufactured using the Creality 3D CR 10s5 machine, based on FDM technology. Indeed, many literature contributions stress the fact that FDM suffers from staircase effect and high porosity, rough surfaces, air leakages and overall low accuracy which may affect the sound [3]. However, FDM technologies have been tested to prove with experimental tests that FDM is not the best technology to be used in musical instrument manufacturing.

3 Sound recording and quality evaluation

After the manufacturing process has been completed, all the five mouthpieces have been tested by an expert musician and professional trombone player. To obtain high-quality recordings, the sound has been acquired in a professional recording studio using a certified Rode NTK microphone, a Motu 8pre USB amplifier system and a 44100 Hz sampling frequency for better sound post-processing (Fig. 6). All the recorded tracks have been saved in.WAV format. The musician played the same short track, of almost 1-min duration, repeating it for all the five available mouthpieces. At the beginning of

Table 1 Alternative mouthpieces tested

Mouthpiece labels	Description of its characteristics
#1	Commercial brass mouthpiece ($a=32.5$ mm, $b=33.8$ mm)
#2	Shape of commercial mouthpiece ($a=32.5$ mm, $b=33.8$ mm), SLA technique
#3	Decreased cup volume ($a=25.1$ mm, $b=29.6$ mm), SLA technique
#4	Shape of commercial mouthpiece ($a=32.5$ mm, $b=33.8$ mm), FDM technique
#5	Decreased cup volume ($a=25.1$ mm, $b=29.6$ mm), FDM technique

Fig. 6 Recording studio

each track, the musician played a musical extemporization characterized by six long notes for better sound analysis. Being available the.WAV music file for each mouthpiece, all the tracks have been analyzed in detail.

There are some variables or external disturbances which will be not taken into account in this study for simplicity such as how hard the performer was blowing air into the mouthpiece. It can be a challenging task for a performer who is changing rapidly between components to maintain consistency of approach in his performance. This is why, in certain other studies, machines have been constructed to replicate the human blowing process, so that more consistent results can be achieved. However, since the scope of this work is to investigate the possibility to use additively manufactured components in an innovative and unusual sector as the musical one, for simplicity this variable will be neglected in the following.

In the following, based on the methodology shown in Fig. 1, three experts in music (a musician and two Professors of Music) have been interviewed to evaluate the sound quality of the recorded five tracks, played within a high-quality stereo. Each expert listened to the five tracks three times and gave a score from 1 to 10 for each mouthpiece test, where 1 stands for insufficient sound quality, while 10 stands for extremely good sound performance. The results of the Comparative Mean Opinion Score (CMOS) are shown in Fig. 7 for each test and each expert. The mean score value for each mouthpiece and its standard deviation have been evaluated.

3.1 DOE study: 2^k factorial analysis

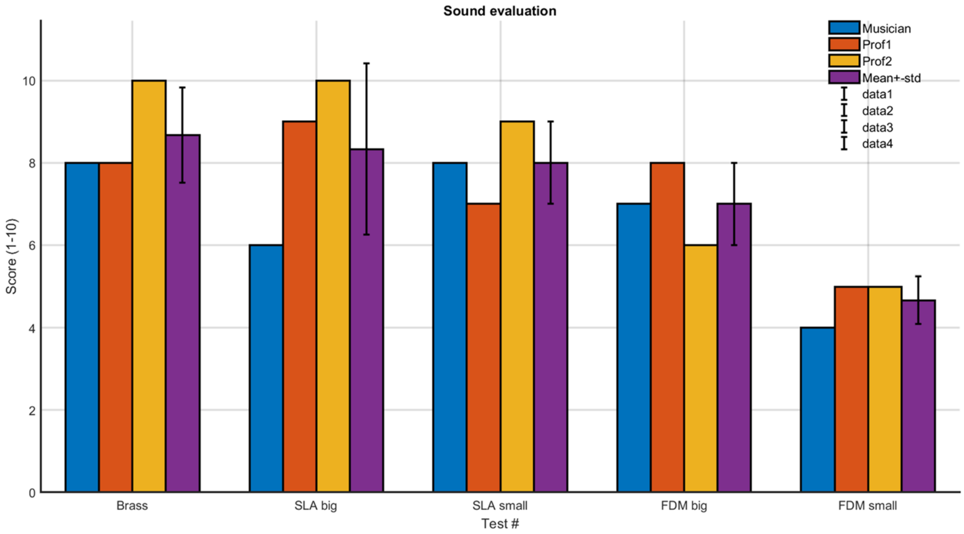
In this section, the application of the DOE methodology to the case study is described, and all the results are reported. The DOE analysis aims to understand which factor is more relevant to the sound quality produced by trombone mouthpieces made by AM techniques. Such an approach is useful to understand if some correlation exists between material and cup dimensions to get good sound quality and to select the best additively manufactured component to be compared with the brass one in the following stage, specifically the sound analysis.

Applying the general flowchart shown in Fig. 2 to this case study, the factors x_i are the AM technology and the cup dimension, while the output y_1 was associated with the sound quality evaluation of three music experts. Even if the expert's subjectivity may affect the output value, this choice is made to associate to each mouthpiece a single numerical value that is directly linked with the sound quality.

3.1.1 Design degrees of freedom

The input parameters in the DOE analysis are called factors and, referring to this case study, they are the material and the cup geometry. Since a 2^k factorial analysis is applied, where

Fig. 7 Comparative mean opinion score of the sound quality of five mouthpieces



$k = 2$, the possible combinations of inputs are 4. Such kind of analysis can be applied when for each factor only two levels are present. In this case, the levels are:

- AM technology: SLA/FDM
- Cup dimension: big/small

As previously mentioned, the output of the analyzed process is the sound quality evaluated by three experts in music, with a score from 1 to 10. More complex analyses involving more than 2 design parameters could be carried out extending the methodology herein described.

3.1.2 Statistical analysis

The DOE analysis is performed in the Minitab software. 3 replicates were selected to respect the number of experts who evaluated the sound quality. Minitab returns a worksheet with all the 12 possible combinations, and the user must fill the output column by himself.

After the statistical DOE testing is set, the methodology shown in the flow chart in Fig. 8 is used.

A first iteration where both the factors [material (A) and cup dimension (B)] as well as their interaction AB has been considered. Then, thanks to the factorial regression study, we found that AB interaction doesn't affect strongly the output: this can be noticed in the Pareto graph or with the *P* value-coded coefficients. If a factor has a *P* value lower than 0.05, its contribution to the output is not significant for the process under analysis. Neglecting the interaction term, the analysis becomes more straightforward, and the results are easier to understand.

3.1.3 Results

Neglecting the mixed term, the statistical DOE analysis is run again, and the regression analysis is performed. The Pareto graph shows that the material factor is more important and relevant to the sound quality compared to the cup geometry dimensions (Fig. 9) (Pareto graph detailed treatment can be found in [38]).

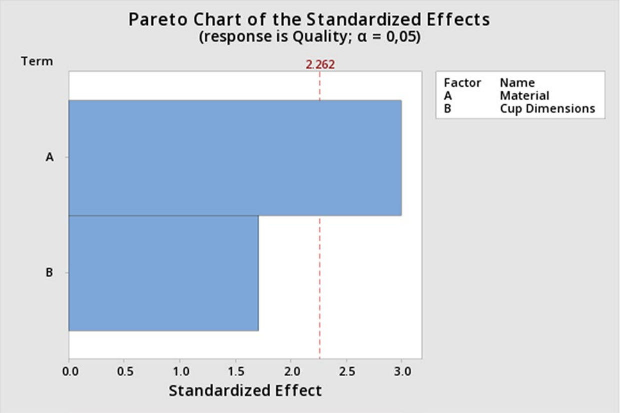
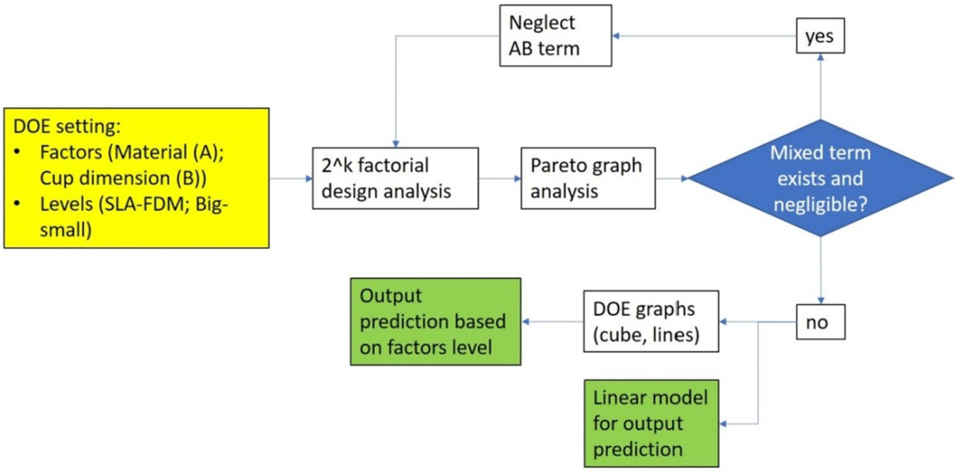


Fig. 9 Pareto chart of material and cup dimension factor effects on the output; only the factors which reach the red line are relevant in the analyzed process

After the detection of more relevant factors, Minitab allows understanding which is the output value (the predicted sound quality) depending on the chosen levels of the two factors in a graphic way, thanks to the factorial plots, which are reported in Fig. 10.

From the results shown on the left in Fig. 10, it can be easily seen that the material factor is more relevant compared to the cup geometry on the sound quality, which agrees with the Pareto graph. Moreover, the SLA material gives a higher output value compared to the FDM and a bigger cup volume may be a better design choice to achieve high sound quality. From the cube plot (see Fig. 10 on the right), the best combination seems to be a mouthpiece made with SLA technology with big cup dimensions, while the worst combination is the selection of FDM technique and small

Fig. 8 Statistical DOE analysis methodology applied for the specific case study



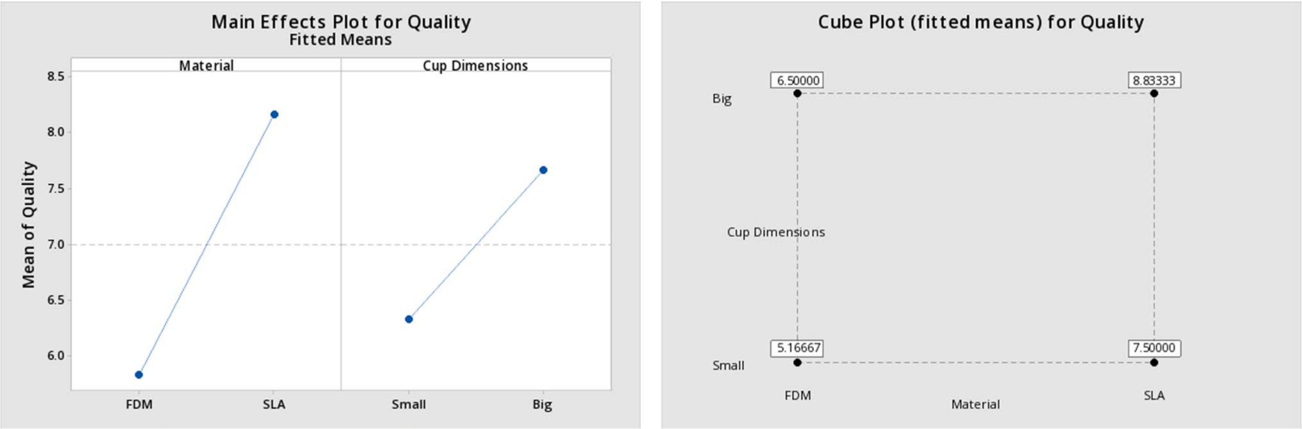


Fig. 10 Statistical DOE analysis results: output prediction based on level values of each factor: the main effect plot, where mean sound quality is plotted for each factor level connected by a line (left); the cube plot, used to show the relationship between factors on the mean sound quality score (right)

cup volume. However, looking carefully at the results, the coupling FDM-big cup dimension gives a satisfying value in terms of sound performances. Therefore, for sake of the following methodology stage (additively manufactured mouthpieces compared to the brass one), both SLA and FDM versions with big cup dimensions will be considered. The small cup design, whatever is the material, leads to poor sound performances according to the expert's assessment. If the statistical analyses are carried out in a good way, the sound analysis confirms that the sound differences from brass and FDM versions are higher compared to the SLA and commercial brass comparison.

3.2 Sound and psychoacoustic analysis

Sound analysis has been performed in MATLAB, thanks to its Audio Toolbox, developed to post-process and compare sounds both in terms of conventional and psychoacoustic parameters. The mouthpieces #1, #2 and #4 have been analyzed, being available the.WAV sound files from studio recordings.

At first, a lowpass filter with a cut-off frequency of 15 KHz has been implemented in the code to delete possible high-frequency bias and noise. Such frequency value is chosen according to the upper limit of the audible range of an adult human ear, according to what suggested by literature [39].

Then, a qualitative comparison in the time domain has been carried out to evaluate the track repeatability along with all the tests. The recorded audio files are of the 'double' type format with 64 bits-per-sample. Using the *audioread* MATLAB function to read the recorded signal, the output vector refers to the normalized amplitude with values between − 1 and 1.

After the analysis of the sound amplitude plot in time (Fig. 11), it is possible to see in the second half of the track that the highest amplitude values are reached with the commercial brass version. In the case of SLA manufacturing, a 28% decrease compared to the brass mouthpiece in the $A(t)$ plot can be noticed. On the other hand, the FDM shows a sound with a lower amplitude in time, suggesting a low-intensity sound (referring to the track portion highlighted with the red circle), with a 67% peak amplitude reduction.

Moving to the frequency domain and looking at the frequency spectrum diagram (Fig. 12), the reader can visually notice that the spectra are similar qualitatively. This means that the sound performances are consistent when AM is chosen as the production process for musical instrument components. Moreover, extracting the amplitude peaks visible in Fig. 12 in the frequency spectrum (taking as lower threshold an amplitude value of 1800), it can be said that these peaks are located at the same frequency values for the brass and SLA mouthpiece (a non-inclusive list is: 234, 353, 468, 707, 886 Hz). On the other hand, some of these frequencies contribute to a lower wave amplitude in the FDM mouthpiece, especially at 234, 353 and 886 Hz. This behaviour can be attributed to the out of tuning of the FDM component due to the difficult management of the mouthpiece by the player which was perceived by the experts in music who evaluated the tracks.

However, above the 2 KHz frequency signals, the energy distribution into frequency components of the signal contained in the spectrum (the subplot area) is lower for both the SLA and FDM mouthpieces compared to the commercial one. This issue is more evident considering the Power Spectral Density (PSD) which describes the signal's power as a function of frequency per unit frequency. For contributions higher than 2 KHz, the energy and therefore the power contained in the waves is higher for the brass mouthpiece

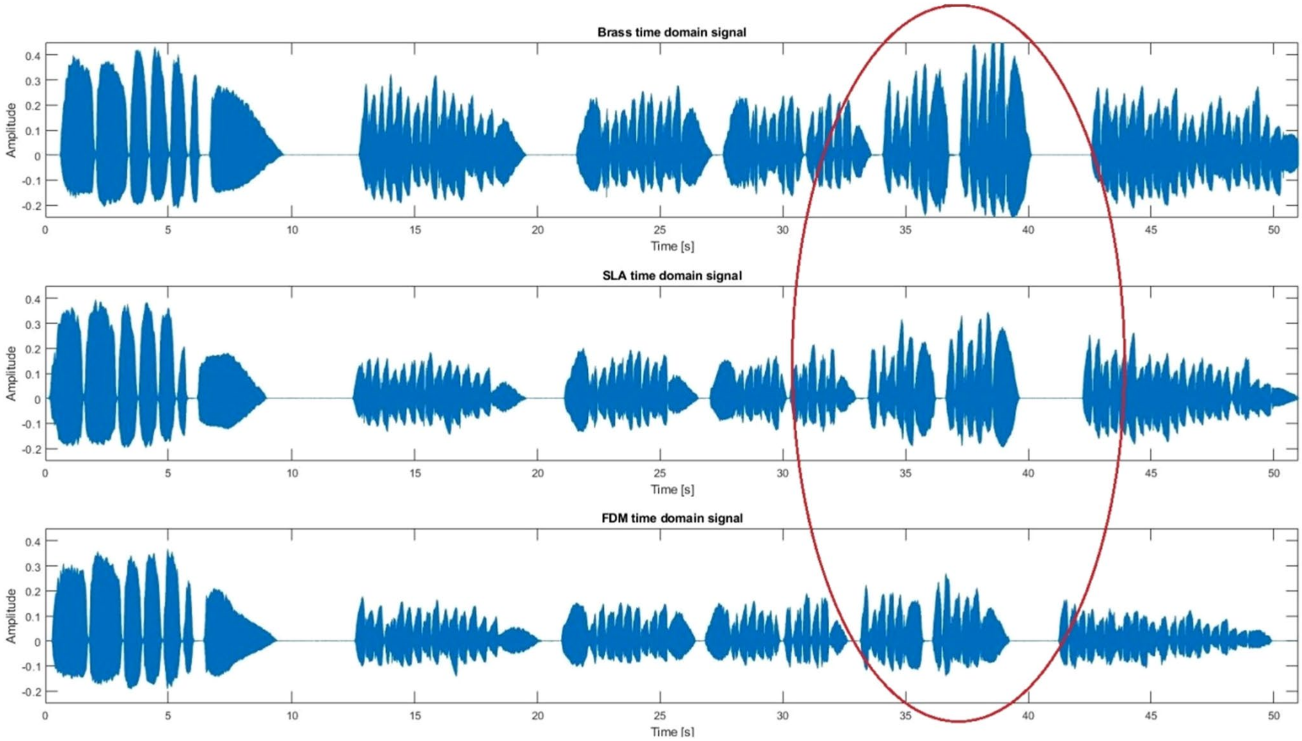


Fig. 11 Sound amplitude in the time domain. From the top: brass, SLA and FDM mouthpieces

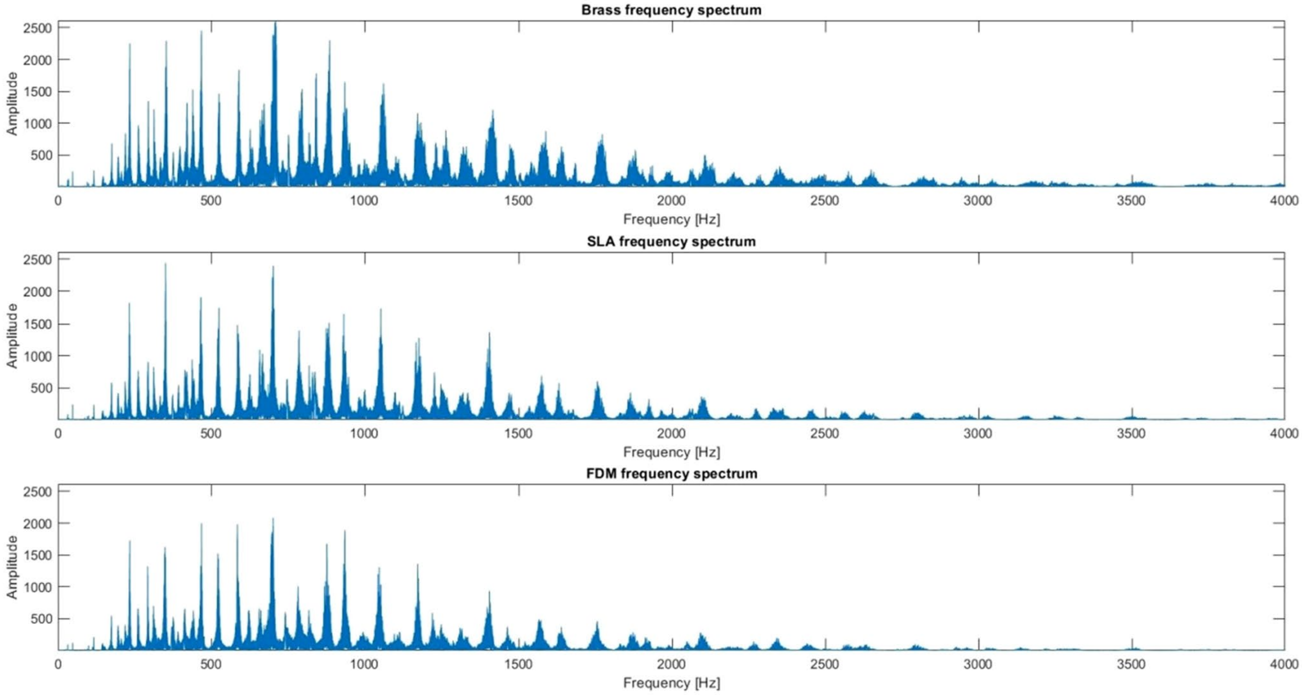


Fig. 12 Frequency spectrum: from top to down: brass, SLA and FDM mouthpieces

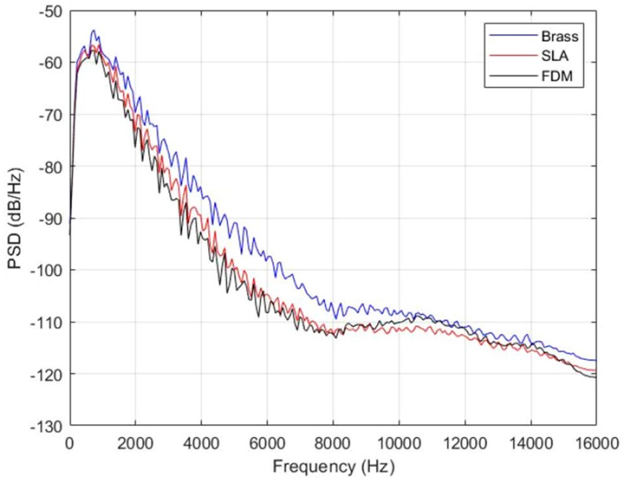


Fig. 13 Power spectral density distribution as a function of frequency

(Fig. 13), while lower (and similar) for SLA and FDM components.

As previously stated, a mathematical tool to evaluate the "distance" between two signals is the cross-correlation function. It has been evaluated that the maximum of the cross-correlation function is located at almost 0 time-shift for both brass-SLA and brass-FDM cases. However, the brass-SLA correlation value is slightly higher compared to the brass-FDM (304 vs 289) meaning that the test's reproducibility is generally good for both additively manufactured components but the mouthpiece produced in SLA shows a more similar temporal amplitude envelop compared to the brass piece: this is in agreement with the DOE approach.

In the frequency spectrum, the time domain is completely lost: a better and complete sound overview is shown in the spectrogram (Fig. 14). From a visual comparison, it can be noticed that spectrogram features are repeatable between the tests using different mouthpieces in terms of temporal events but less in power content. Indeed, it can be detected a lower power content in the additively manufactured mouthpieces (already highlighted with the PSD plot), with a more relevant difference at the high frequencies (fewer portions of spectrum in yellow colour). However, once again, this difference is more evident in the second half of the FDM spectrogram highlighted with a red circle in Fig. 14. Moreover, it is possible evaluating the harmonics occurring at whole-number multiples of the fundamental frequency.

Similar results can be obtained from the spectral centroid plot, which is evaluated in time for the played tracks. The centroid behaviour has several similitudes among the three versions under investigation, as can be seen in Fig. 15. However, a slight difference can be noted: for instance, the peak value at around 37 s in the track for the FDM mouthpiece is lower than brass and SLA components (12% of difference of the FDM one compared to 0.7% of the SLA version). The spectral centroid is usually associated with the brightness of a sound; therefore, it is frequently used in digital audio processing as an automatic index of musical timbre. The higher is the spectral centroid

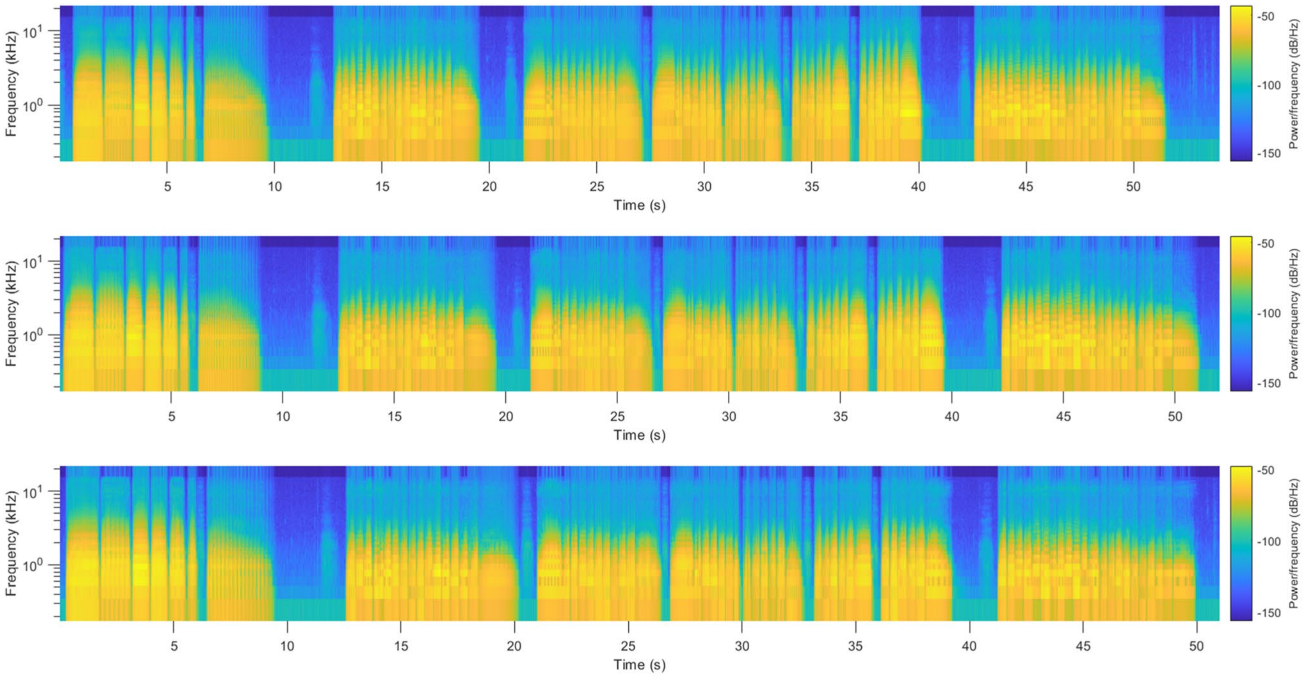


Fig. 14 Spectrograms: from the top, mouthpieces #1, #2 and #4

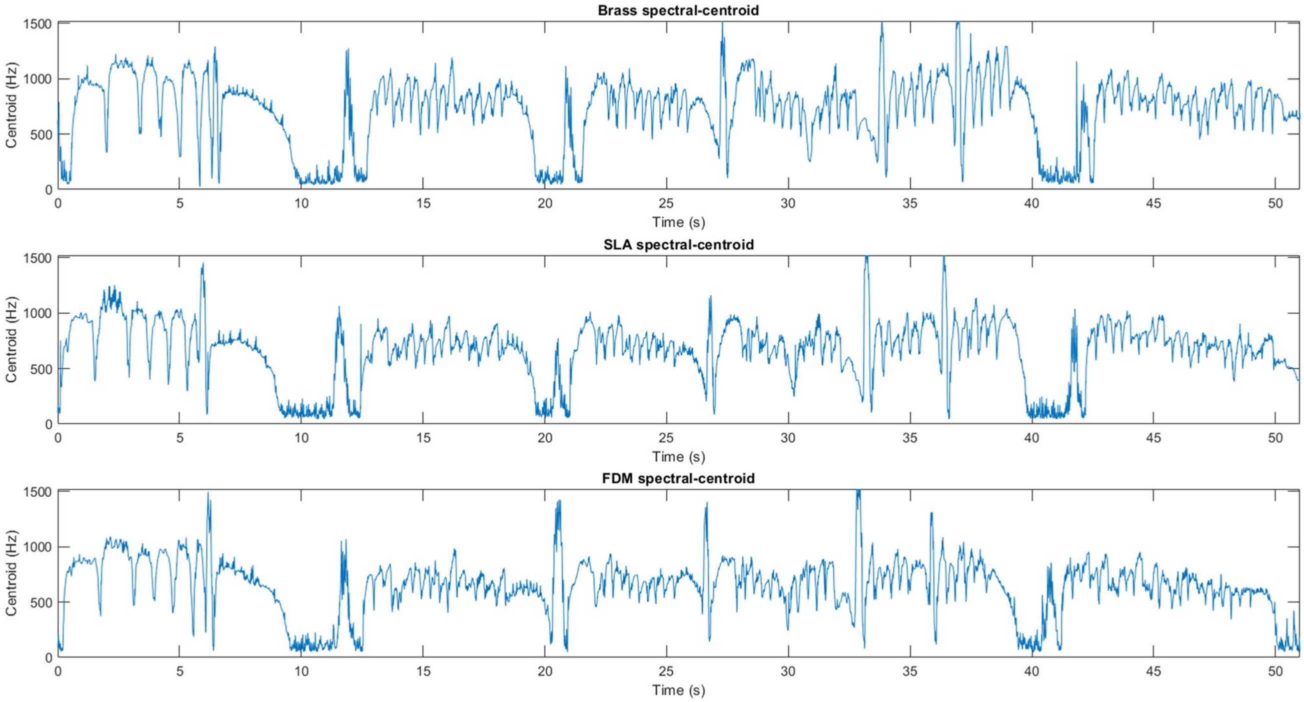


Fig. 15 Spectral centroids in time: from the top, mouthpieces #1, #2 and #4

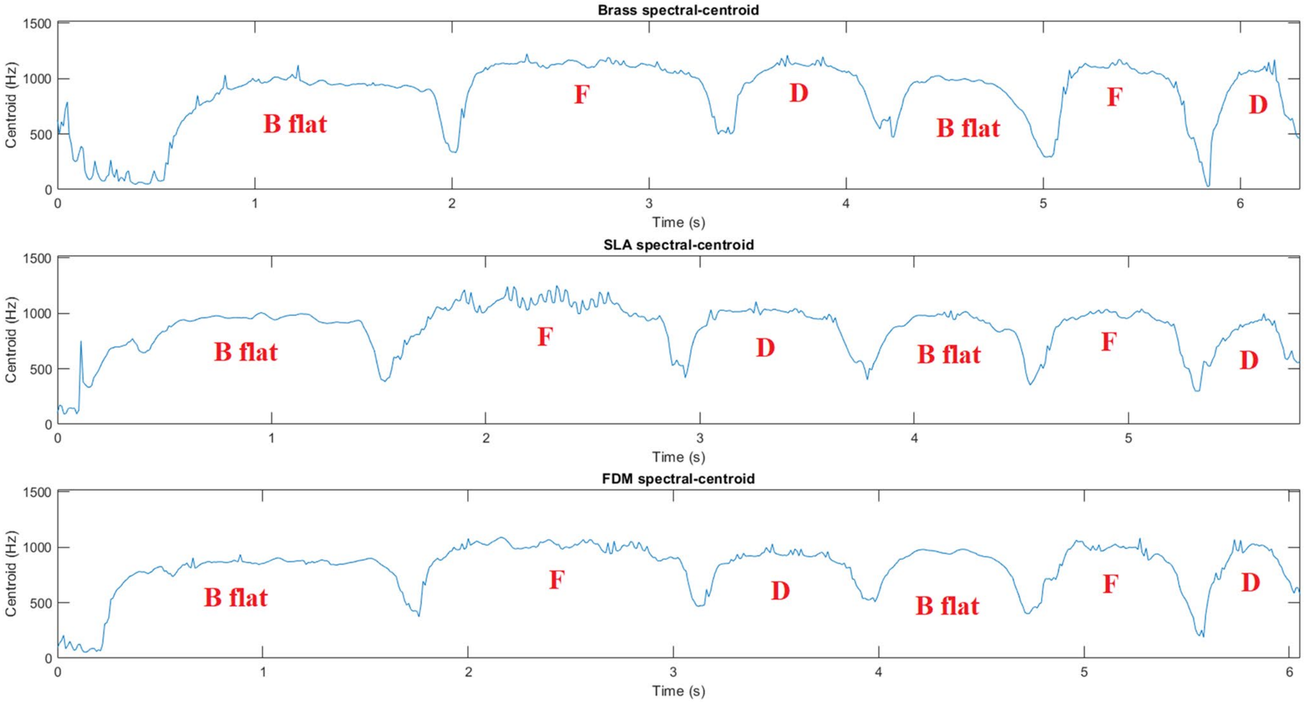


Fig. 16 Particular of the spectral centroid in time: from the top, mouthpieces #1, #2 and #4

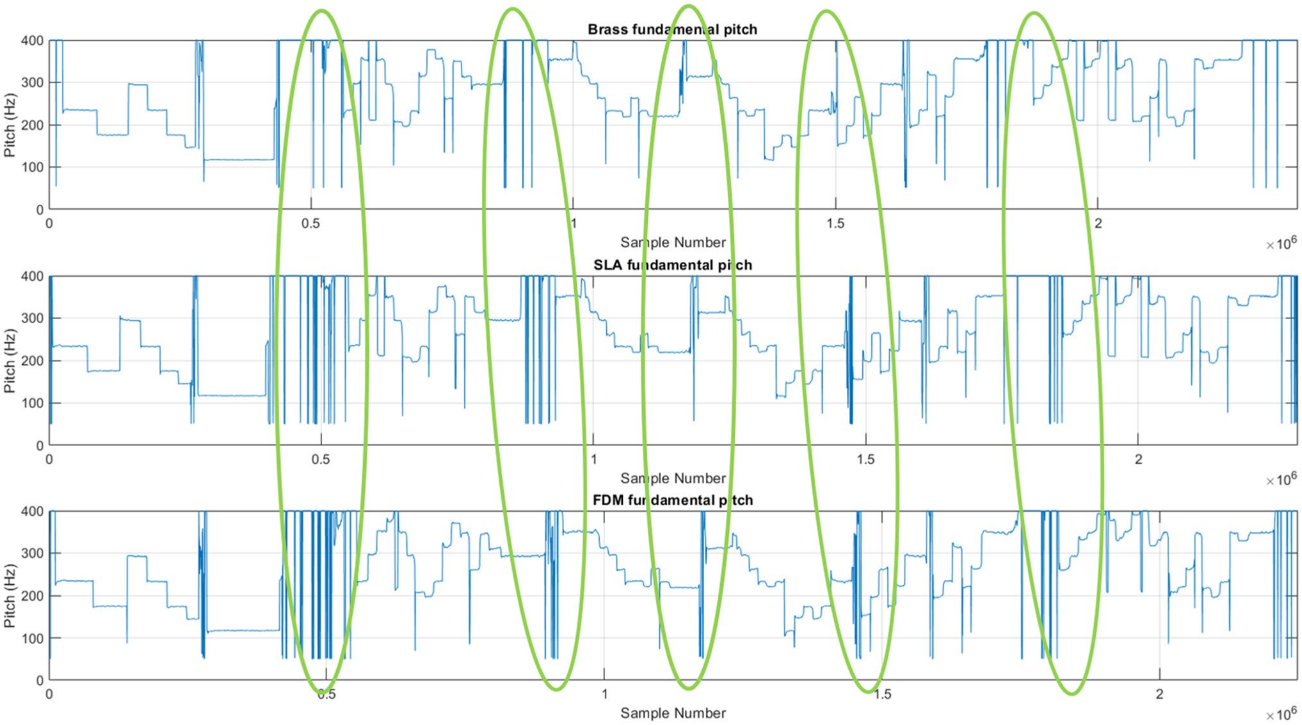


Fig. 17 Fundamental pitch distribution: from the top, mouthpieces #1, #2 and #4

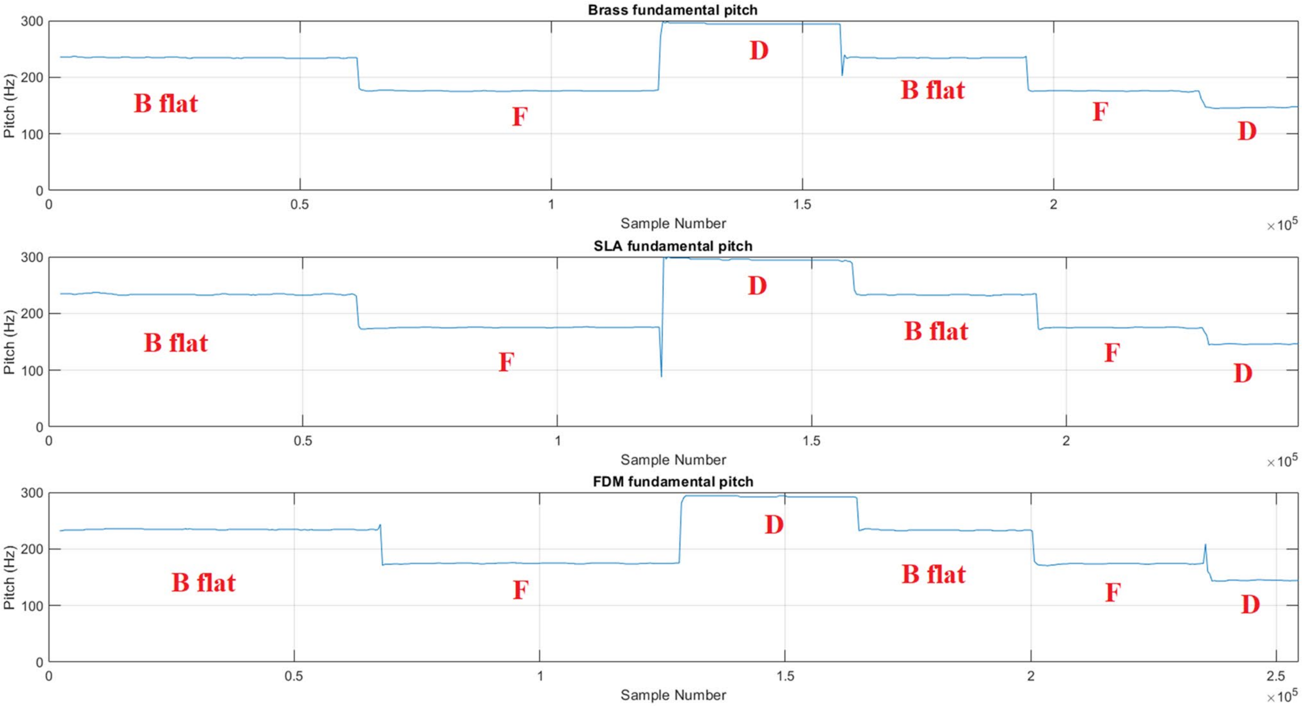


Fig. 18 Fundamental pitch distribution of the first 6 notes: from the top, mouthpieces #1, #2 and #4

value, the higher will be the brightness perception of the sound.

The same result in terms of spectral centroid can be shown focusing on the first six notes played by the musician at each track (Fig. 16). These notes are, respectively: B flat, F, D, B flat, F and D (of the lower octave). The overall time behaviour is similar, but mouthpiece #4 has 4 of the 6 notes with a spectral centroid peak value of several percentage points lower compared to the commercial and the SLA mouthpieces. It means a lower timbre when compared to the other brass and SLA items.

As the last conventional audio signal analysis, the fundamental pitch is evaluated for all the versions under comparison. As can be seen in Fig. 17, there are five regions, highlighted with green circles, in which there are some pitch discrepancies, where the brass version has a clearer pitch distribution without disturbances, even if in general a similar behaviour among the three mouthpieces behaviour can be noticed.

However, if the analysis focuses on the first 6 notes played by the musician (Fig. 18), it can be noticed that almost the same values in terms of fundamental pitches can be found. This means that in general AM results in components that have sound characteristics close to parts produced with traditional manufacturing (mean $err_{\mathrm{FDM}} = 0.81\%$, mean $err_{\mathrm{SLA}} = 0.66\%$).

Also, a psychoacoustical approach has been used to study the acoustic features of musical sound: several parameters, such as loudness, sharpness, fluctuation strength and roughness, have been considered, according to definitions introduced in Sect. 2.

Figure 19 illustrates the behaviour of time-varying loudness measured in sones (one sone is arbitrarily set equal to the loudness of a 1000 Hz tone at a sound level of 40 dB above the standard reference level) for all the tested mouthpieces, computed according to the algorithms included in ISO 532-1 regulation [18]. Neglecting the effect of the time-shifting of the brass played track (yellow line), it is possible to see that the trombone with brass mouthpiece has higher loudness levels during all the played track compared to the SLA and FDM mouthpieces (respectively, in orange and cyan colour). The difference between metal commercial and experimental instruments increases during the audio signal. Moreover, following all the previous analysis, the worst performances are obtained with the FDM component, while the SLA manufacturing guarantees a sufficient sound volume.

Moving to the fluctuation strength parameter, computed according to the approach described in [32], Fig. 19 shows almost comparable behaviour of brass and SLA mouthpieces during the played tracks, while the FDM version has lower performances, especially at 25 s played time, confirming the evaluation carried out with other indicators. Afterwards, when the time-varying sharpness—that is evaluated following standards DIN 45692 and ISO 532-1 [31]—is considered, there are some peaks in correspondence of pauses

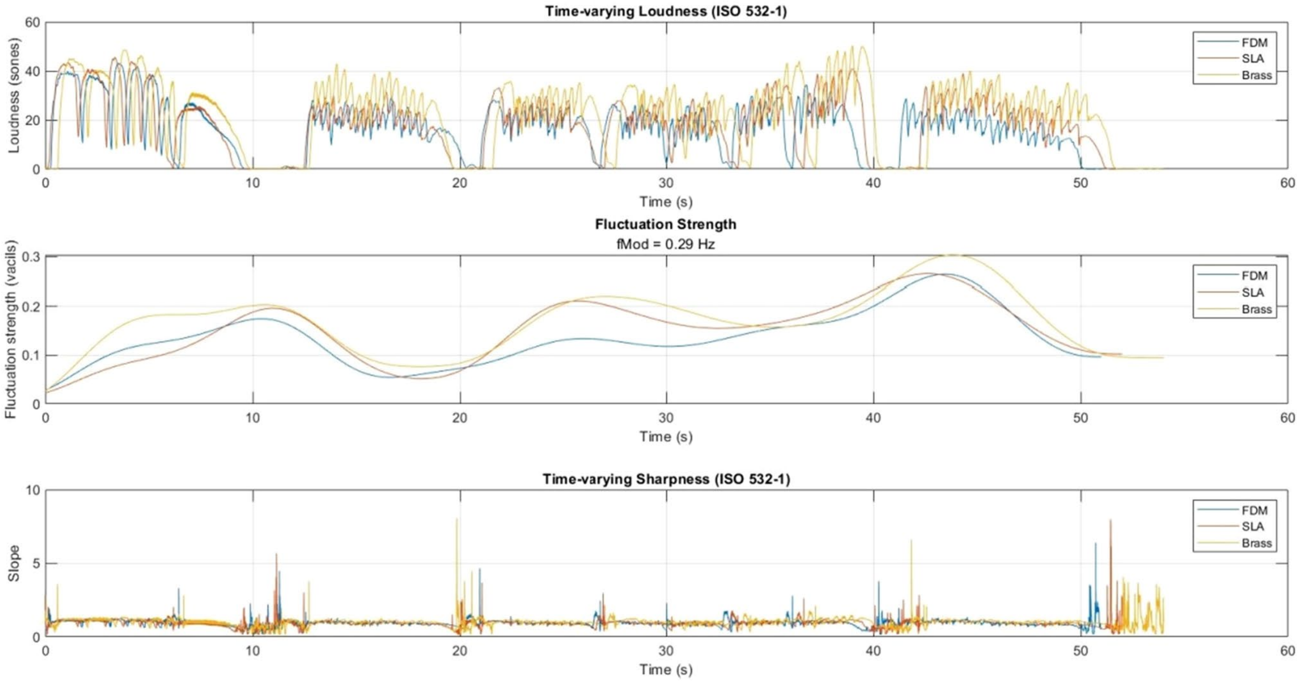


Fig. 19 From the top, time-varying loudness, fluctuation strength and time-varying sharpness distribution for the brass (in yellow), SLA (in orange) and the FDM (cyan) mouthpieces

Table 2 Psychoacoustic average performances of tested mouthpieces

	N5 loudness (sones)	Average fluctuation (vacil)	Average sharpness (acum)	Average roughness (asper)
Brass	42.58	0.169	0.953	0.3879
SLA	39.76 (– 6.6%)	0.151 (– 10%)	0.927 (– 2.7%)	0.429 (+9%)
FDM	35.70 (– 16%)	0.135 (– 20%)	0.941 (– 1.2%)	0.464 (+16%)

made by the player during the played tracks. These could be associated with environmental noise in the recording room which increases instantaneously the sharpness level. Leaving out these peaks, all three mouthpieces have a comparable amount of sharpness level during the audio signal and no important conclusion can be drawn from this kind of analysis.

Just to provide the reader with an easy and fast comparison among psychoacoustic parameters for the tested mouthpieces, the N5 percentile of the loudness level in sones (a level below which is 95% of the reported loudness), the mean sharpness level (in acum), the mean fluctuation strength (in vacils) and the mean roughness level (in asper) are collected in Table 2 along with the percentage error compared to the brass mouthpiece which is taken as a benchmark. The meaning of these measurement units can be found in reference [18]. For what concerns the roughness estimation, this metric has not yet been standardised, which reflects on several proposed methods of calculation. This is due to the difficulty of accurately quantifying the perceived masking depth. In this research, the Daniel and Weber algorithm [34] is used to estimate the total roughness level of the audio signal.

From the psychoacoustic analysis, it is possible to state that the brass mouthpiece has the highest level of acoustic sound quality. AM variants show worse performances in absolute value, but the SLA version has negligible performance difference (less than 10% of error) in terms of all the analysed psychoacoustic parameters (Table 2).

The conclusions that can be drawn from the sound and psychoacoustic analysis are that on the one hand, FDM technology offers poorer sound performances compared to SLA, remarking and confirming the results coming from the statistical DOE analysis which are in agreement. On the other hand, the SLA mouthpiece has demonstrated sufficient sound quality performance after analysing several audio signal parameters. To sum up, the exploitation of SLA in future applications can be justified by the customization possibility offered by AM technology and good sound qualities. SLA can be considered a good technology to design and produce extremes and innovative components for musical instruments without losing acoustic and sound quality performances. Moreover, thanks to the methodology described in this study, new and experimental designs of musical instruments manufactured in AM could be easily compared with commercial pieces.

4 Conclusion and future developments

The aim of this paper is the development of a methodology that can be used to compare and evaluate the musical performances of musical instruments produced with traditional and new manufacturing technologies based on additive manufacturing techniques. The methodology relies on a Design of Experiment approach to understand which design factor is more relevant in terms of sound quality. In the following, digital sound processing is accomplished in terms of time and frequency domain analysis by applying several mathematical tools, such as frequency spectrum, spectrogram, cross-correlation, spectral centroid and fundamental pitch function. In parallel to conventional audio signal analysis, psychoacoustic parameters are computed to compare the acoustic sound quality of tested components.

Even if authors acknowledge that some variables in the complex relationship between musician and instrument where not taken under consideration, the conclusion stemming from this research is that AM processes, especially SLA, are a good alternative for the production of the musical components from a merely design and manufacturing perspective. Indeed, the sound characteristics are not overturned by the change in material and production process, even if plastic material or photo-sensible resins are used instead of metallic materials, particularly when SLA technology is used. Moreover, AM allows for extreme customization capability compared to traditional manufacturing techniques. When AM is adopted, symbols, writings or other distinctive symbols can be added to musical instruments, increasing end-user satisfaction. Rapid changes to the geometry of musical instruments can be made, by changing the 3D Computer-Aided Design (CAD) model before the production process. Finally, plastic material does not suffer from glueing of lips when playing wind instruments on cold winter days, as it happens when brass or other metals are used, making AM very attractive.

Further studies involving wave propagation in the air, perception by the human ear and neural stimuli should be made in future works. Other temporal, harmonic, perceptual and spectral audio descriptors will be investigated in future works to quantitatively evaluate the timbre of AM components. Moreover, other studies involving different musical instruments should be carried out to confirm AM maturity about the production of musical components; in this scenario, this work can be considered a preliminary contribution towards that direction.

Acknowledgements Authors wish to thank the following students of Mechanical and Aerospace Engineering at the School of Engineering and Architecture of the University of Bologna for their support of the research: Michele Ascani, Luca Crudeli, Lisa Lucci, Sarah Merighi, Davide Neri and Giovanni Santucci. A special thanks to the expert musician and professional trombone player Mr Lorenzo Rocculi, who played the musical pieces and two Professors of Music.

Funding Open access funding provided by Alma Mater Studiorum - Università di Bologna within the CRUI-CARE Agreement. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability Neither data, material, nor code is available due to future work in the same project.

Declarations

Conflict of interest No potential conflict of interest was reported by the authors.

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