Reproducing Musical Instrument Components from Manufacturers' Technical Drawings using 3D Printing: Boosey & Hawkes as a Case Study.

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Abstract

This paper demonstrates how component musical instrument parts can be recreated from manufacturers' technical drawings using 3D printing (Additive Manufacturing) technology. While the application of this technology to produce either component parts or entire musical instruments is not new, such approaches usually involve working from extant models, using Computer Tomography (CT) scanning to produce images that can then be converted into code readable by a 3D printer. However, models of this kind are often in museums or private collections and are thus not always easily accessed, even for research purposes. In this project we used surviving technical drawings of a range of clarinet component parts, originally manufactured by the Boosey & Hawkes company, to reconstruct such parts without recourse to surviving models. In particular, two different mouthpieces were printed using a variety of different printers and tested by professional performers on instruments for which the original mouthpiece designs were intended. We successfully demonstrated that this non-invasive technique can be used to 3D print musical component parts in those instances where original plans survive, even when extant component parts do not. We also demonstrated through qualitative feedback from professional musicians that hand finishing of 3D printed mouthpieces remains essential for skilled performers, because of the very fine tolerances that are accepted as part of professional performance.

Key Words: 3D Printing; Clarinet Mouthpieces; Boosey and Hawkes; Technical Drawings.

Word Count 6030

Introduction

Musical instruments demonstrate particular confluences of human creative endeavour and technological advance. Indeed, developments in the design and production of instruments are often at the forefront of technological innovation in whichever culture they arise. For example, the significant increase in both the variety and quantity of brasswind instruments produced in mid-nineteenth century Europe reflected not only the growth of military music-making predicated on colonial expansion, but also specific developments in valve technology and the introduction of steam-powered manufacturing processes that facilitated cheaper and swifter production (Haine, 1985). The recent evolution of 3D printing provides a similar example of a technological innovation that is increasingly being put to the service of musical instrument production (among its many other uses), and one that is likewise partly allied to changing performance frameworks. Also known as Additive Manufacturing, 3D printing was developed during the mid-1980s to create solid object industrial prototypes through the successive layering of different materials, but today it is used to produce or reproduce many different objects, from high-performance racing-car components to human body parts. It has already been shown to be effective when applied to musical instrument production. Zoran (2011) has used the process to produce an entire flute, while Howe, Shahbazmohamadi et al. (2014) have reproduced ophicleide and saxophone mouthpieces and a recorder foot-joint. Savan and Simian (2014) have similarly printed entire cornetts and appropriate mouthpieces for them, and Mark Witkowski has reproduced an eighteenth-century French church serpent in the University of Oxford's Bate collection.[1] Internet searches also reveal a burgeoning amateur scene, with enthusiastic individuals attempting to print working trumpets, saxophones, flutes, and a variety of component parts. Although smaller instruments and their parts have been most widely reproduced, more recent examples include entire guitars and violins.[2]

With respect to professional musical performance, it is unsurprising that much of this work has focused on the reproduction of instruments associated with what is loosely described as 'early music', a term usually understood to mean music of the European

[1] See http://www.bate.ox.ac.uk/serpent.html (accessed 6 May 2019), from which the files for this replica serpent may be freely downloaded.

[2] A range of different 3D printed guitars can be found at https://all3dp.com/2/3d-printed-guitar-10-best-curated-models-to-3d-print/, while one version of a 3D printed violin may be seen and heard here https://www.3d-varius.com/3dvarius-features/

classical tradition written prior to c.1750. As a result of the growing interest in historically-informed performance styles of this music, increasing numbers of musicians are playing period instruments and/or reproductions of them, to recreate what are taken to be the performance aesthetics prevailing at the time the instruments themselves were current. The need for reproductions is easily explained. Original instruments of the period in which a specific piece was composed may be rare, and even when they survive they may not be in a playable condition, with one or more component parts broken or missing. Some instruments are regarded as sufficiently valuable that they are carefully preserved in museums or private collections. In such cases access to them can be difficult, and borrowing them for use in particular concerts often impossible. The potential benefits for individual musicians to create instruments or missing component parts using Additive Manufacturing, thus circumventing some of these problems, are easy to see.

Various 3D printing techniques have evolved over time, including Stereolithography (SLA), Selective Laser Sintering (SLS) and Fused Deposition Modelling (FDM). Stereolithography builds the object in a vat of liquid polymer. The polymer is hardened where a moving computer-controlled laser beam strikes it, and thus the object is constructed layer by layer. Selective Laser Sintering uses a powder bed fusion process: a very thin layer of powdered polymer is put onto a building platform, and then the particles in the shape of the first cross-section of the object are fused together by a laser, or sometimes using UV light. The platform is then lowered one layer's depth and the process is repeated with each layer fused upon the one below. Fused Deposition Modelling is the cheapest and most widely used process. The object is built up in layers using a thermoplastic filament that has been heated to its melting point and extruded. A more recent printing technique has been developed by the American company, Carbon 3D. Originally designated as Continuous Liquid Interface Production (CLIP), but now known as DLS (Digital Light Synthesis), the process mixes both ultra-violet light and oxygen to grow 3D parts continuously from a small vat of liquid resin. This is cured during the printing process to become a Rigid Polyurethane object. The printing time is claimed to be 25-100 times faster than traditional printers and produces a smooth surface which more closely resembles that of injection moulding (see Tumbleston et al., 2015).[3]

[3] The TED talk given by the inventor of this process, Joseph DeSimone, can be viewed at https://www.ted.com/talks/joe_desimone_what_if_3d_printing_was_25x_faster#t-660886

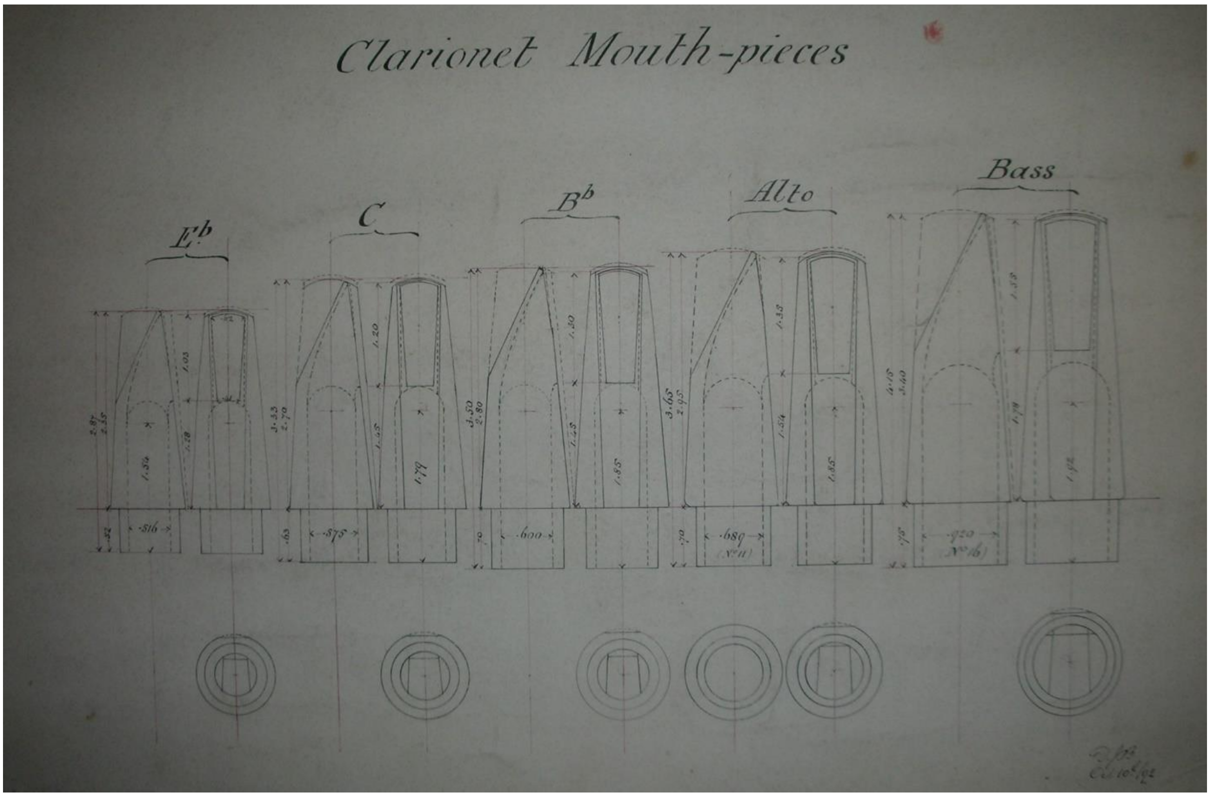
A variety of 3D printers are now available, ranging from highly sophisticated machines designed for complex industrial tasks to more basic devices designed for domestic use. Printing services are easily accessible online and an increasing number of bureaux offering this service are being established. Most 3D printers are too small to build entire instruments, so the reproductions are constructed in pieces. However, they are an ideal size for parts such as saxophone, clarinet and brass instrument mouthpieces and similar components. The most common approach thus far has involved scanning extant instruments or component parts using Computed Tomography (CT), which generates 3D computer images (Doubrovski, Verlinden, Geraedts, Horvath, & L. M. Konietschke, 2012; Lorenzoni, Doubrovski, & Verlinden, 2013; Howe, Shahbazmohamadi, Bass, & Singh, 2014). These Computer Aided Design (CAD) images are then converted into file formats containing the G-code commands used to control the 3D printers. If CT scanning is not possible, then the instruments can be measured by hand, with CAD files made up from these measurements. But measuring instruments in this way is time-consuming and requires particular skill to achieve sufficient accuracy, especially if details such as bore proportions or the internal dimensions of mouthpieces are required. And as already noted, many legacy materials are held in museums or private collections, and thus access to these materials can be difficult, particularly if they are fragile or their locations geographically distant.

The purpose of this project was to see whether this approach could be applied to reproduce clarinet mouthpieces even in cases where no original mouthpieces might be available, meaning that CT scanning could not be undertaken. Instead, we used technical drawings held at the Boosey and Hawkes archive in London, which contained the detailed original designs for particular component parts that the company manufactured.

Boosey and Hawkes

For much of the twentieth century, Boosey & Hawkes (B&H) was arguably the most well-known and internationally successful British music company. Formed in 1930 from the merger of Boosey & Company and Hawkes & Son, the company became renowned both for its music publishing activities and as a manufacturer of musical instruments. In its heyday the company was a musical icon of the British Empire, with sales to British military regiments stationed around the world resulting in the global distribution of its products. At home it provided numerous bands and orchestras with woodwind and brass instruments and, especially in the 1960s, developed many student models for use in education. In many ways, therefore, the company helped shape the sound of British music, a sound that was often internationally recognised as distinctively ‘British’, with certain iconic models – such as its renowned 1010 clarinet – still used and valued by performers today.[4]

Following a series of failed business ventures, and an accounting scandal at one of its subsidiary companies in 2000, the company went into decline and entered receivership in December 2005. Between 2003 and 2005 a large amount of surviving corporate material was acquired by the Horniman Museum in South London.[5] This included not only instruments and component parts, but also stock books detailing production and sales patterns–thus revealing what kinds of instruments and parts were made for whom–and a large number of the company’s historical technical drawings (see figure 1). A selection of the latter provided the starting point for the present project.



[4] For more information on the Boosey and Hawkes company and its manufacturing history see Brand, 2013 and Howell, 2016.
[5] Boosey & Hawkes held a collection of historic musical instruments, which was purchased by the Horniman Museum in 2003, aided by grants from the National Art Collections Fund and Heritage Lottery Fund. The firm’s surviving technical drawings were donated to the Horniman in 2004, followed by additional plans, the factory workbooks, and other literature and items when Besson, the sole remaining subsidiary of Boosey & Hawkes, went into liquidation in December 2005. See also Strauchen-Scherer & Myers, 2007.

Figure 1 B&H technical drawing of clarinet mouthpieces (1892)

Many of B&H's instruments remain in circulation, and although component parts such as mouthpieces are no longer manufactured, they can often be acquired on the second-hand market. Inevitably, the number of such instruments and parts available reduces over time, through natural wear and tear, breakages and losses, etc. We therefore wanted to demonstrate, on a 'proof of concept' basis, that we could reconstruct component parts directly from the original technical drawings using 3D printing, without reference to legacy materials.

Naturally, the drawings used by manufacturers are usually accurate, detailed and drawn to scale (see figure 2).

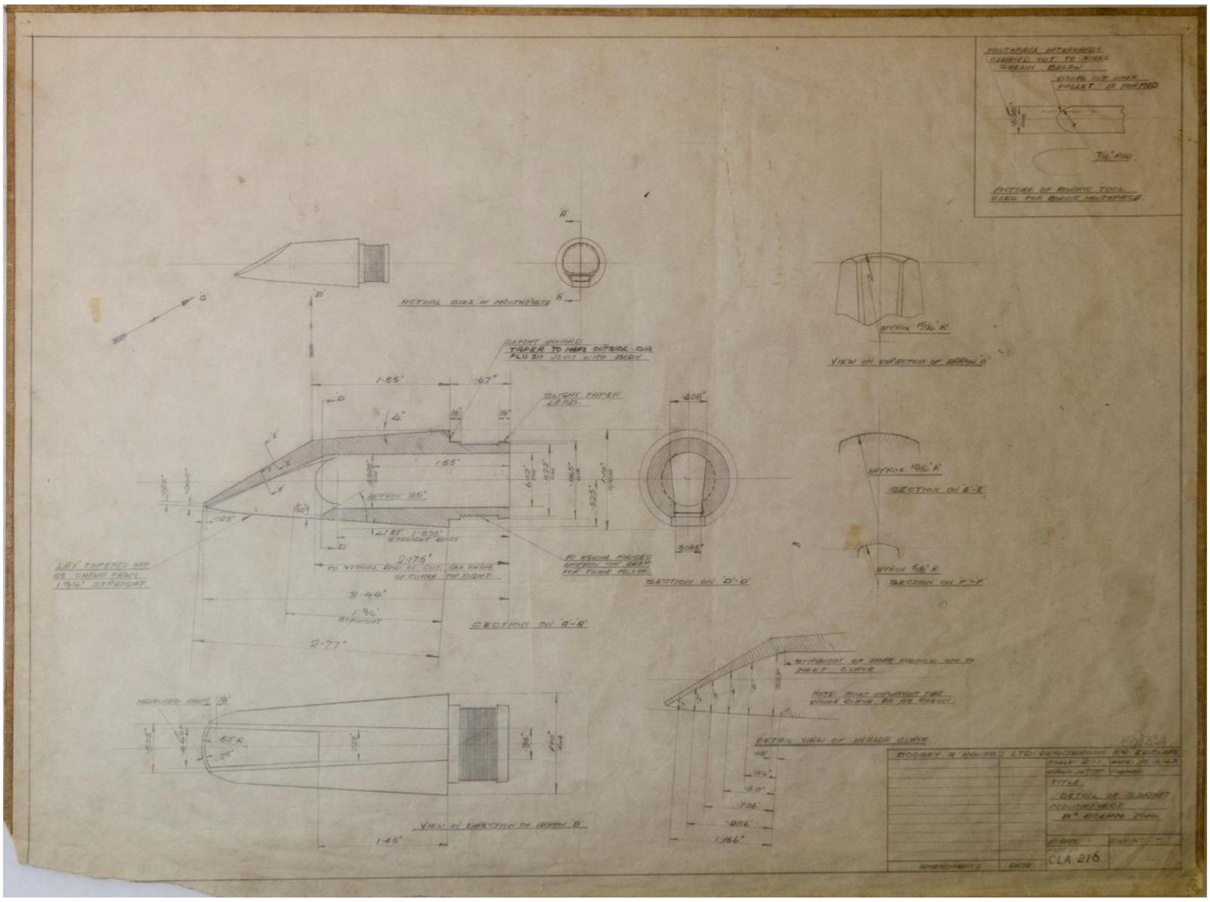


Figure 2: Technical drawing for 1943 Bb Boehm 1010 mouthpiece

They contain all the necessary measurements needed to manufacture instruments in the traditional fashion. With these detailed plans, we felt that it should be possible to transcribe the information they contained into 3D CAD models, which could then be used to print 3D components. We focused on clarinet mouthpieces, in part because this reflected the expertise and performing experience of the investigators, but more importantly because we could involve in the project professional performers who were very familiar with B&H clarinets. The performers also recognised the potential value of 3D printing for constructing instrument component parts, and were well acquainted with the notion of the 'English' clarinet sound to which B&H instruments had contributed.

The materials used for clarinet mouthpieces have changed over time. Until the early nineteenth century, fruitwoods or boxwood were generally used, but these mouthpieces suffered from water retention and would deteriorate relatively quickly. Over the course of that century, hardwoods such as ebony and grenadilla imported from various European colonies became more popular, and occasionally glass (crystal) or metal mouthpieces could also be found. By the end of the century, hard rubber (ebonite) was starting to be used, and this has become the most common material utilised today, although glass, metal and occasionally wooden mouthpieces can all still be found. Notwithstanding the current ubiquity of ebonite, therefore, performers are aware that mouthpieces might be made of other materials, and some players will have experience of using these.

The mouthpiece is crucial because it provides the link between the player's oral cavity and the air column contained within the body of the instrument. This air column is excited by the reed attached to the mouthpiece, and thus the oral cavity, lips, reed and mouthpiece form a complex and delicate coupled system that plays a critical role in determining the timbre and pitch of the note produced. Minute variations in the behaviour of a mouthpiece can have a disproportionate impact on the feel of that mouthpiece for the performer and thus the sound that emerges. Yet, acoustic theory suggests that the material from which a mouthpiece is made should have no bearing on its acoustic performance, and that the internal dimensions alone determine how it functions. Performers, however, will often assert that they can hear the difference between two mouthpieces that are identical but made from different materials, and they certainly feel those differences. Similar arguments have been put forward in relation to the materials used to construct the body of the instrument (Benade, 1976, pp. 499-501). In his thesis on clarinet mouthpiece design, Edward Pillinger notes that:

> The listener may not be able to detect any difference between an instrument made from plastic, ebonite, resin, metal or wood, but most clarinettists insist that they can both feel and hear a difference, however small. These same clarinettists display an even greater awareness and sensitivity to mouthpieces made from different materials (Pillinger, 2000, p. 129)

Methodology

Various drawings from the Boosey & Hawkes Archive were identified and selected as suitable for this project. These included a 1943 Bb Boehm 1010 clarinet mouthpiece and a 1977 J. Brymer 'Type B' Symphony 1010 clarinet mouthpiece. In keeping with the 'proof of concept' approach taken here, both a barrel and a bell from the 810 model of clarinet were also reproduced. The latter components were not subject to further qualitative testing because we did not have an 810 model to work with, and the barrel in particular would have been designed quite specifically for that model.[6] The 1010 mouthpieces were chosen because their design (with a parallel bore) was specific to that particular model of clarinet. Other more common designs are not compatible with it. The 1010 clarinet, which was developed in the early 1930s in response to the increasing move of British players from simple to Boehm system instruments,[7] rapidly became associated with what is now recognised as an English style of clarinet playing. The instrument had a wide bore and was generally characterized by a large and free-sounding tone which enabled many players to produce a full, expressive vibrato. There is no evidence in the B&H workbooks to suggest that the 1010 was an entirely new design; records indicate that improvements were made to existing clarinet models 200 and 201. But it was one of the most successful professional instrument models that B&H manufactured. Although it has not been produced for over 30 years and musical fashions have changed, there are still many clarinettists who continue to play it, and thus the production of working replica component parts for this model is relevant for current and future players.

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[6] The barrel of a clarinet is that part of the instrument which sits directly below the mouthpiece, into which the latter fits. Its name derives its gently curved exterior walls, which resemble a barrel. Its proportions are carefully matched to the bore proportions of the clarinet model for which it is designed. The bell is the final (distal) part of the instrument, furthest from the player's mouth. Although it is a distinctive visual feature of the instrument it plays relatively little role in determining the sound quality, except for those notes which use the longest available tube, such as the instrument's lowest notes. For other notes the sound largely emanates through what is known as the tone-hole lattice, that is, those tone holes that are left open by the particular fingering used to produce any given note .

[7] For more on the application of the Boehm fingering system to the clarinet see Hoeprich, 2008, pp. 171-175.

It was not possible to scan the technical drawings *in situ* at the museum, so high-resolution digital photographs were taken. CAD models were then drawn up from the detailed measurements on the drawings using the programme Solidworks. The Solidworks files were exported as stereolithography (STL) files and then Simplify3D was used to print these from a 3D printer.[8] Whilst the barrel and bell were straightforward to construct in CAD, the mouthpieces were more of a challenge. Most of the information on the plans was straightforward to transfer. However, owing to the limitations imposed by working from measurements alone, a few problems were encountered: the internal bore of the 1977 mouthpiece was originally created by Boosey & Hawkes using a specific tool with a dedicated tool number (T30719 Gauge No. 02349). As the dimensions of this tool were not known, the photographed image of the original drawing was placed over the CAD image in order to achieve results as close to the plan as possible. There was also a lack of uniformity in the decimal places used to record the dimensions on the plans. Some measurements were accurate to the micron (0.001mm) while others were less detailed. In places where the original measurements were not accurately recorded, measurements had to be deduced. In addition to replicating the internal bore dimensions and the overall external dimensions, one of the key points was endeavouring to replicate the lay.[9] Together with the internal dimensions of the chamber, this has the greatest bearing on the sound produced, because of the way it interacts with the reed and the couple formed in the player's mouth.

[8] Simplify3D translates a 3D model into horizontal slices and printing instructions for the printer.
[9] Single reed instruments such as the clarinet work by blowing air past a reed that is attached to a mouthpiece. The sound is produced by the reed opening and closing rapidly in a percussive action. The manner in which the mouthpiece curves away from the reed in order to facilitate this action is known as the facing, or lay. Both this lay, and the stiffness of the reed used, are critical in generating this percussive effect and the particular timbral qualities that arise.

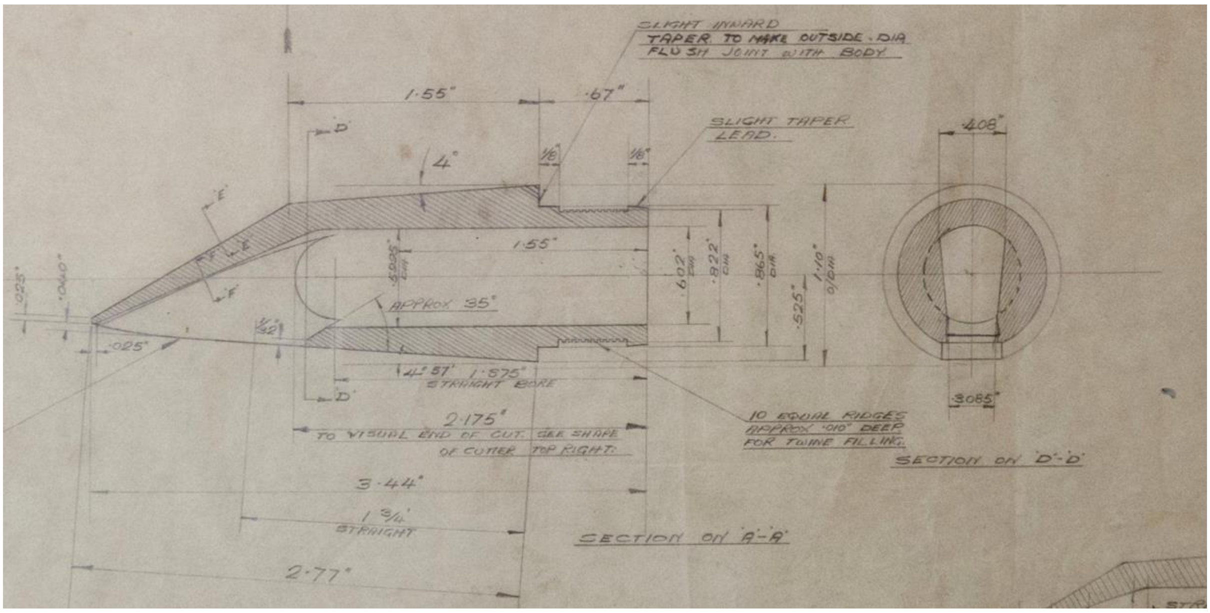

Figure 3: Technical drawing for 1943 Bb Boehm 1010 mouthpiece (detail)

The clarinet mouthpieces, barrel and bell were printed using four different 3D printers, as detailed in table 1. Two mouthpiece prints were produced from the Ultimaker 2 printer, which uses the Fused Deposition Modelling process. The printing material selected was ABS (Acrilonitrile Butadiene Styrene), a low-cost, opaque thermoplastic polymer, used for engineering (and making Lego bricks). Six prints were made from each of the more sophisticated Objet500 and EnvisionTEC machines. Objet500 uses the polyjet technique in which nozzles on the printhead jet fine droplets of liquid photopolymer and support material to make a thin layer; the photopolymer solidifies instantly when exposed to a specific intensity of UV light. The layers are built up until the model is complete (this method is similar to the stereolithography process, but thinner layers can be created). Polyjet printing materials are particularly suitable for use where accurate detailing and smooth surface finish are required. Four model printheads and four support printheads were employed for printing the components, and the printing material selected was a rigid opaque plastic, VeroWhite, an acrylic based photopolymer. Support material was a gel-like substance that was removed using a water jet. EnvisionTEC Perfactory printers build models from liquid resin using a Direct Light Processing (DLP) projector. The projector cures tiny volumetric pixels. The material used for printing the clarinet components was R11, a high-grade acrylic-based resin. This process creates a very smooth finish. The final method was to use continuous liquid interface production (CLIP) technology developed by the Carbon 3D company, from which we printed a further six mouthpieces. This rather different method employs digital light projection and oxygen permeable optics which act on liquid resins to produce an object which is then drawn out of the resin in its complete form, rather than built up in layers as with other additive manufacturing methods. It is noticeably quicker than the other methods. Table 1 gives an overview of the different processes employed, and some indication of the times taken to print the various components.

Table 1: Printing details and timings

Printer	**Process**	**Material**	**Layer height**	**Prints**	**Length of time taken to print**
Ultimaker 2	Fused Deposition Modelling	White ABS (Acrylonitrile Butadiene Styrene - thermoplastic polymer)	0.1mm	1x1943 m'pce 1x1977 m'pce 1x barrel 1x bell	1943 m'pce: 3 hrs. 1977 m'pce: 3 hrs barrel: 4 hrs bell: 8hrs 15mins
Objet500	Polyjet	VeroWhite (acrylic based photopolymer)	Z 16 microns, X-Y 42 microns	3x1943 m'pce 3x1977 m'pce 1x barrel 1x bell	Four items printed in a single build: 8 hrs 45 mins
EnisionTEC Perfactory	Digital Light Processing	R11 (ruby red) (acrylic-based liquid photopolymer)	Z 50 microns X-Y 32 microns	3x1943 m'pce 3x1977 m'pce 1x bell	Two mouthpieces and barrel printed in a single build: 13 hrs 40 mins
Carbon3D	Digital Light Synthesis)	RPU (Rigid Polyurethane)	n/a	3x1943 m'pce 3x1977 m'pce	Single build 3hrs

Results

3D printed mouthpieces can be quite rough and are not necessarily useable in their raw state. Some of the mouthpieces printed as part of this project were therefore finished by a clarinet mouthpiece specialist, Ed Pillinger. This finishing process is quite critical in relation to the final dimensions of the mouthpiece, and particularly to the way in which a mouthpiece feels and responds in the player's mouth, since minute differences in the disposition of reed and mouthpiece can have significant effects on the resultant sound.

The mouthpieces were also accurately measured before and after they were finished. These measurements are given in Tables 2 and 3.

Table 2: Mouthpiece measurements: 1943 Bb Boehm 1010 mouthpiece

	Vero Control Unfaced	Vero Control 2 Unfaced	Vero Faced	Carbon Control Unfaced	Carbon Control 2 - Unfaced	Carbon Faced	Ruby 43 Faced
***Tip opening**	0.98	0.8	0.96	0.89	0.9	0.82	1.04
****Feeler gauge**							
0.04	23	20	21.5	22	20/21	20/23	16/18
0.1	18	14	17	16	15.5/16	16/17	13/14
0.3	12	9	11	10	10	10/11	9
0.5	7.5	5	7	5.5/6	6	05/06	6/6+
0.8	3	1	2/2.5	1	2.0/2.1	1.2/1.3	3

Table 3: Mouthpiece measurements: Jack Brymer ‘Type B’ Symphony 1010 mouthpiece

	Vero Control Unfaced	Vero Control2 Unfaced	Vero Faced	Carbon Control Unfaced	Carbon Control2 Unfaced	Carbon Faced	Ruby Control Unfaced	Ruby Control2 Unfaced	Ruby Faced
***Tip opening**	1.12	0.98	1.12	1.16	1.17	1.1	1.02	1.1	1.04
****Feeler gauge**									
0.04	18/19	16	18	20/25	20	L18 /R19	16	18	16/18
0.1	14	14	15	15/16	15	15 /15+	13	14	13/14
0.3	10	10	10	11/11.5	11	10/11	10	10	9
0.5	7	6	7	8	8	7	6	7	6/6+
0.8	4	2.75	4	4/5	4+	3.5/4.0	3	4	3

*The measurement in millimetres between the centre of the tip of the mouthpiece and the reed.
** Measurements in millimetres from the tip rail to where a feeler gauge comes to rest under calibrated glass. This indicates the distance between the reed and the mouthpiece at that point. Larger numbers in column 1 indicate a greater distance from the tip of the reed. Two numbers in any other box indicate asymmetry (that is, different readings on each side of the mouthpiece at the same distance from the tip).

As can be clearly seen in these two tables, there are small but critical differences between prints of the same mouthpiece using the same printer and material, for example, in the differences between the unfaced Vero control and unfaced Vero control2 in Table 2. Given the variability inherent in the printing process on the same machine, it is therefore unsurprising that there was also variability across the different machines and materials, notwithstanding that all prints were generated from the same code. This indicates how variable the results of the 3D printing processes can be. Pillinger noted to us that 'none [of the mouthpieces] come very close to any of the engineering drawing measurements except maybe one'.

In addition to the detailed quantitative information derived from careful measurements made during the process, we also sought qualitative feedback from two professional clarinettists who were familiar with B&H instruments, Alex Allen and Tony Lamb.[10] Time constraints meant that we were unable to test every print, but at least one version of each printing method was tested, in both finished and unfinished versions. A selection of comments drawn from their responses to the variety of mouthpieces that they tested are offered in Tables 4 and 5.[11]

Table 4: Qualitative feedback on 3D-printed unfaced 1943 mouthpieces

Mouthpiece	Observations
Ultimaker 2 + ABS	(1) Tip rail serrated. Lay is very one dimensional – Very close [i.e. the reed closes up against the mouthpiece too easily]. Thin uncontrolled sound. Only works on 'blastissimo'! [i.e. when blown very hard]. Needs somebody to wave their magic wand over it and face it. You might have more success than me…but I found it far too close. (2) Very, very close and can't really be played normally. It makes a sound, but a thin sound.
Objet Polyjet + VeroWhite	(2) Again it's very close, but it's an improvement on the first. (1) Amazing that you can play something that hasn't actually been faced. (2) Maybe with a facing that would be feasible.

[10] Alex Allen was using pre-war B&H 1010 model while Tony Lamb was also using a 1010, albeit one from the early 1970s.
[11] A full transcript of the comments offered during the testing session is available on the *JNMR* website. Comments attributed to the performers have been deliberately anonymized both here and in the appendix.

	(1) They have used acrylic for mouthpieces in the past. Just instantly that feels like a nicer resistance. The mouthpiece itself possibly, or the material. It's got more tone. (2) Potentially that could have quite a nice tone. (1) [after changing reed to 2½] I could do a concert on that. It's a 1931 clarinet so this '43 mouthpiece matches intrinsically. Felt like quite a comfortable marriage - mouthpiece and clarinet (2) [now on 2½ reed] It's not quite comfortable but it's got potential. The harmonics are right. (1) Something appealing in the sound. (2) It's got a sound you wouldn't be ashamed of if you made something like that in a concert.
Carbon3D	(2) Tone is not unlike previous mouthpiece but the control is not as good. Basic tone is ok. As soon as you do anything at all with the embouchure [the sound] just disappears. (1) It's not even. The rails are completely shot. It's a bit 'agricultural'! I think it's because the tip rails aren't even.

Table 5: Qualitative feedback on 3D-printed faced 1943 mouthpieces

Mouthpiece	Observations
Objet Polyjet + VeroWhite 1931 facing	(1) Wow! Lovely! It's quite an open lay he's put on that. Comfortable, but lacks core. I had to reign it in a bit. But that's lovely. (2) The thing with all these experiments is…it's like when you are looking for reeds with your own mouthpiece…the reed is so critical. The wrong reed can give you a totally false impression of what the mouthpiece is like. It's got quite a resistance. It feels a bit wide, but it doesn't feel as though there's enough containment. It doesn't have enough core. The core sound is not as good as at least one of the others.
Carbon3D 1931 facing	(1) A tiny bit bright in the clarion [upper] register. But it's ok down in the chalumeau register. But I think that is a successful partnership in terms of mouthpiece and clarinet. (2) Slight difference in the way we blow. You take a bit more of the mouthpiece in your mouth possibly. Maybe that affects certain areas more…
EnvisionTEC + R11 1931 facing	(1) That's 'Zingy'. So different. I can't hold it back, it's so bright. There's no depth. The minute you try and broaden the sound you just hit a wall. This is my least favourite. What we call in the trade a 'glasscutter' [i.e. very penetrating]. Lacking sonority. Out of my comfort zone.

	(2) It's got a certain quality in the sound. Sweet sound. Maybe good for chamber music. [This mouthpiece suited this performer better] (1) It suits you much better. It's got an immediate response.

Such comments demonstrate that although the differences in the measurements of these mouthpieces may be very small, they are keenly felt by skilled performers. Small differences between component parts, and the different materials from which they are constructed, can produce quite different sonic results. And inevitably, different musicians playing on rather similar set-ups can have quite different subjective responses to the same piece of instrument technology. During the testing session of our mouthpieces one performer noted that he was 'always fiddling around with ligatures' to which the other replied, 'I invariably find I have to change ligature when I change mouthpiece'.[12] All of which is a reminder that an important component of instrumental sound production is the conception of individual sound that is in the performer's head, and which they are trying to reproduce (see Cottrell, 2004, pp. 44-55). The technology involved, whether reeds, mouthpieces, barrels or ligatures, are only tools to enable them to produce that sound, and a performer may over time produce similar sounds using quite different equipment.

Conclusion

This project demonstrated that useable clarinet mouthpieces could be successfully and cost-effectively recreated from surviving technical drawings using 3D printing, thus circumventing the need to scan existing legacy materials. Although the supply of historic technical drawings like those in the Boosey & Hawkes Archive may be limited, such drawings provide a usable basis for the reproduction of instruments or components. It is possible that greater numbers of similar drawings may become available over time, as other companies make historic plans available that are no longer subject to intellectual property rights (IPR). It is also conceivable that this methodology could be used to reconstruct parts from other documents, such as expired patents (again with due regard for IPR implications), in those cases where sufficiently precise measurements are provided. These non-invasive methods of reproduction offer significant benefits for reproducing historic instruments or instrument parts, particularly in cases where legacy materials may be difficult to access; for

[12] The ligature is that part of the clarinet which holds the reed tightly against the mouthpiece.

example, when they are located in museum or private collections, where they may be only available for examination and not for practical use.

Boosey & Hawkes were the dominant musical instrument manufacturing company in Britain during a golden age for British music between c.1890-1950, and for many orchestral players the company's instruments were central to the notion of a 'British' orchestral sound. As the boundaries for historically-informed performance styles are redrawn ever closer to the present day,[13] it is conceivable that wind players may look to recreate the sounds of this period using contemporary instruments or reproductions of 'forgotten' models, including the simple-, Clinton-, and Clinton/Boehm-system clarinets that were popular among British clarinet players until the 1950s. 3D printing of instrument component parts using the information contained in B&H's surviving technical drawings could play an important role in reviving these instruments.

The reproduction of instruments and their components has traditionally relied upon the skill of a small number of craftsmen using bespoke tools and techniques, and it is often a detailed and lengthy process. Today's technology makes at least some of the process easier. It also, to a degree, democratises music instrument manufacture, by making it possible for individuals to produce relatively complex instruments without recourse to expensive tooling and other machinery or casting processes. Nevertheless, whether component parts are generated from technical drawings or from scanning legacy materials, the 3D printing process does not often produce immediately usable objects, and certainly not in relation to the fine tolerances demanded by professional musicians. Mouthpieces in particular usually require hand finishing, to make them smooth enough to be comfortable in the player's mouth and also to ensure a perfectly smooth table (the flat part of the mouthpiece onto which the reed is placed).

The mixed-methods approach taken in this study, using both qualitative and quantitative data sources, has demonstrated the variabilities inherent in this process, both in terms of the production of components and their reception by musicians. This, together with the small-scale nature of this project, makes it injudicious to offer assertions about which particular 3D printing method might produce the best results. The minor variations between different prints of the same mouthpiece, the potential for yet greater variability across different printing processes even when working from the same code, and the subjective

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[13] For example, the Orchestra of the Age of Enlightenment, one of Britain's leading ensembles playing on period instruments, now includes works by Elgar, Sibelius, Strauss, Mahler and other late romantic composers in its concerts. See http://www.oae.co.uk/ (accessed 1 December 2018)

responses of musicians to the microscopic dissimilarities between different materials and components, all make overarching declarations unwise. Our professional performers responded with a range of positive and negative comments about all mouthpieces. The professionally finished mouthpieces unsurprisingly yielded the better responses, with the finished version manufactured from the Carbon 3D Digital Light Synthesis printing system being perhaps marginally the most favoured overall. But one or two of the unfaced mouthpieces produced good results also, particularly the Objet Polyjet printer using VeroWhite. The 'playability' of this unfinished mouthpiece was a surprise to both the project team and the performers. At present, however, the 3D printing process has not generally obviated the need for skilled craftsmen to finish an object to a player's satisfaction, particularly for professional performers.

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