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The Use of Additive Manufacturing for Bassoon Mouthpieces

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i. Abstract (Deutsch)

*Diese Masterarbeit untersucht die Anwendbarkeit von neue Technologien in dem Blasinstrumentenbau durch die Benutzung von additive Fertigstellung (AM) um synthetische Doppelrohrblätter für das Fagott zu bauen. Die Anwendung von neue Technologien hat das Potenzial solche mit traditionelle Doppelrohblattherstellung verbundene Herausforderungen zu lösen, wie schwankende Qualitätsunterschiede, kurze Lebensdauer und lange Bearbeitungsbedarf. Materielle Eigenschaften, Designentscheidungen und Herstellungsmethoden sind die Hauptaspekte die bei der Herstellung von Fagott Mundstücke überlegt sollen. PET-G ist ein Material der für seine geringe Wasseraufnahme und Haltbarkeit bekannt ist, und war deswegen statt den beliebteren PLA für diese Arbeit ausgesucht. PET-G wurde mit der AM Technologie FDM (*Fused *Deposition Modelling) für den Bau des Mundstückes benutzt.*

Die Ergebnisse zeigen, dass AM erhebliche Vorteile in Bezug auf Anpassung, Effizienz und Zugänglichkeit bietet. Es bleiben jedoch Herausforderungen bei der Erzielung präziser Geometrien, der Nachbildung der akustischen Eigenschaften von natürlichem Rohr und der Optimierung der Materialauswahl. Diese Arbeit betont die Bedeutung von Designparametern wie die Verhältniss vom Stapfen zur Spitze (Tip-to-Tube Ratio), den Öffnungsabmessungen und der Rohrblattlänge als Hauptfaktoren, die die Klangerzeugung beeinflussen. Auflösung und Materialkompatibilität wurden als kritische Einschränkungen identifiziert, die die Leistung bei der Verwendung von FDM beeinträchtigen, was darauf hindeutet, dass für zukünftige Forschungen andere AM-Technologien wie SLA oder PolyJet mit alternativen Materialien wie Polypropylen oder SLS-Nylon getestet werden müssen.

Indem diese Studie das Potenzial von AM für die Entwicklung synthetischer Rohrblätter demonstriert, legt sie den Grundstein für weitere Innovationen im Bereich Rohrblattdesign und -herstellung. Sie hebt die transformativen Möglichkeiten von AM in der Produktion von Blasinstrumenten hervor und bietet Musikern und Herstellern verbesserte Anpassungsmöglichkeiten und Zugänglichkeit. Diese Arbeit fördert die intersektionale Nutzung von Materialwissenschaft, präzisem Design und Akustik, um die traditionelle Rohrblattproduktion durch fortschrittliche Technologie neu zu definieren.

ii. Abstract (English)

This thesis investigates the applicability of new technologies in wind instrument by using additive manufacturing (AM) to produce synthetic reeds for the bassoon. Their implementation can potentially solve challenges associated with traditional cane reeds such as variability in quality, short lifespan, and labor-intensive preparation. Material properties, design considerations, and manufacturing methods are the main aspects to consider for the manufacturing of a bassoon mouthpiece. PET-G is a material known for its low water absorption and durability, and was selected over the more popular PLA. PET-G was then processed using the AM technology of fused deposition modeling (FDM) to construct prototypes.

The findings reveal that AM offers significant advantages in customization, efficiency, and accessibility. However, challenges remain in achieving precise geometries, replicating the acoustical properties of natural cane, and optimizing material selection. This thesis highlights the importance of design parameters such as tip-to-tube ratio, aperture dimensions, and reed length as main factors in influencing sound production. Resolution and material compatibility were identified as critical limitations impacting *performance when using FDM, suggesting the need to test other AM technologies like SLA or PolyJet using alternative materials such as polypropylene or SLS nylon for future research.*

By demonstrating the potential of AM for developing synthetic reeds, this study lays a foundation for further innovation in reed design and manufacturing. It highlights the transformative possibilities of AM in wind instrument production, offering enhanced customization and accessibility to musicians and manufacturers. This work encourages the intersectional use of material science, precise design, and acoustics to redefine traditional reed production through advanced technology.

1. Introduction

The rapid advancement of additive manufacturing (AM) has revolutionized countless industries (Jemghili et al., 2020), yet its potential in crafting wind instruments remains largely untapped (Damoradan, 2021). AM, also commonly referred to as 3D printing, converts virtual 3D models created with computer-aided design (CAD) into tangible physical objects (Ligon et al., 2017, p. 1). The technology, developed in the 1980s, offers cost-effectiveness, design innovation, and flexibility as its major advantages (McCausland, 2020; Dixit, 2022). AM enhances the understanding of sound production in wind instruments and serves as a valuable tool for music education (Avanzini et al., 2020). In recent years, AM machines have become increasingly accessible, with several systems available that fit within the average consumer's budget (Thomas, 2016). Over the last two decades, AM technology has advanced significantly, now capable of producing fully functional end-use products, and is commonly used in fields such as biomedical, aerospace, defense, and construction (Mobarak et al., 2023). AM's role in wind instruments is growing rapidly, offering new opportunities for innovation and research (Umetani et al., 2016). Additive manufacturing (AM) is a process that builds objects layer by layer based on CAD data, with model quality and accuracy influenced by factors such as layer thickness, machine capabilities, material properties, and post-processing requirements (Horn & Harrysson, 2012). AM simplifies the creation of complex shapes, excelling in producing objects without the need for tooling (Wa et al., 2015). AM processes typically involve several key steps, starting with creating a virtual model through CAD and ending with the finished part, which may require post-processing for refinement (Gibson, 2015). Additive manufacturing processes are classified into several categories, each involving different methods of material processing, such as liquid vat photo-polymerization, material jetting, and powder bed fusion (Bourell et al., 2017). Choosing the appropriate manufacturing technology for AM depends on machine resolution, material properties, and design feasibility, among other factors (Bucur, 2019).

The bassoon, a wooden wind instrument with a conical bore, serves as the tenor and bass voice of the woodwind section and is played using a double reed (Waterhouse, 2001). The double reed, crafted from a single piece of cane shaped into a tube and secured with wire, produces sound by vibrating when air is blown through the small gap between its two strips (Bate & Bruges, 2001; Campbell et al., 2004). Traditional cane reeds, made from *arundo donax*, require soaking before use, as this process reduces stiffness and adjusts the vibrating frequencies to ensure proper functionality (Ewell, 2017). However, the natural variability of cane affects the predictability of reed quality (Heinrich, 1991). Synthetic reeds, which are unaffected by changes in moisture or temperature, offer a promising alternative, yet their feasibility for double-reed instruments like the bassoon remains underexplored (Légère Reeds Ltd., 2024). Bassoonists face limitations with conventional cane reeds, such as variability in quality, performance, and a short lifespan averaging around one month (Arbiter 2020). According to Heinrich (1991), the quality of raw materials is a critical factor in crafting high-quality reeds, as poor raw material can result in unplayable or suboptimal reeds. Although technological advancements have introduced synthetic options, these have not yet achieved widespread acceptance among bassoonists (Bucur, 2019). This thesis explores the use of AM to produce synthetic reeds for bassoonists, aiming to address challenges in replicating the acoustical properties of traditional cane reeds by manufacturing a functioning prototype using the technology.

The process of manufacturing synthetic reeds using AM involves challenges in material selection and design to match the density, stiffness, and vibration properties of natural cane (Kopp, 2003). The main factors in choosing the methods of AM were to identify the smallest features the machine can handle, pick the right material for the process, and ensure the design works for production (Bikas et al., 2019). Quick damping, a characteristic essential for ending notes cleanly in reed instruments, is another critical factor to replicate (Speck & Spatz, 2004). By integrating advanced manufacturing techniques with musical needs, as demonstrated by the work of companies like Légère Reeds Ltd. (2024), this research has the potential to transform reed production, making it more accessible and customizable. Additionally, it could save bassoonists significant time spent on customizing their reeds and preparing them for use (Heinrich, 1991). Fused deposition modelling (FDM) technology has become a popular choice for developing prototypes and functional end-use parts in research due to its simplicity, affordability, and the availability of raw materials (Cano-Vicent et al., 2021). Recent studies on AM in musical instrument research show promising results, including the work of Ozdemir et al. (2021) and Rodríguez et al. (2023), who explored AM's application in mouthpieces for clarinet and trombone. These studies evaluated prototypes with the help of expert musicians, a method we will also apply during the construction and evaluation of a double reed mouthpiece for bassoon. No substantial academic research has focused on double-reed instruments such as the bassoon (Bucur, 2019).

PET-G emerges as a suitable material for applications involving liquid exposure, such as in the maritime and packaging industries, or creating a double reed (Moreno Nieto et al., 2021, 3). The question of toxicity is of extremely high importance since the chosen material is placed directly in the mouth of the player, and environmental impacts shouldn't be neglected either (Belloncle et al., 2012). This study attempts to design and test a 3D-printed bassoon reed, focusing on acoustical performance and playability. This thesis argues that additive manufacturing can be used to produce a functioning synthetic reed for the bassoon, if design and material challenges are addressed.

The thesis is organized into six chapters. In the first chapter the basic concepts and aims of this thesis are laid down. In the second chapter introduces the relevant background on the bassoon and its double reed, traditional and newer reed manufacturing methods, and additive manufacturing technologies with special focus on wind instruments. In the third, the chosen methods for the manufacturing of the synthetic reed are described in the categories of material, design and chosen AM method. In the fourth chapter the synthetic reed is evaluated in a semi structured interview by an expert bassoonist, as well as a comparison between a cane reed and the synthetic reed is done with the help of spectral analysis. In the fifth chapter the results are discussed by identifying the key strengths and weaknesses of the synthetic reed while also proposing improvements for future designs, material and AM technology selection. In the last chapter conclusions are drawn based on the first five chapters.

2. Background

2.1 History of the Bassoon

The bassoon is a wooden wind instrument with a conical bore, played using a double reed, that serves as the tenor and bass voice of the woodwind section (Waterhouse, 2001). Double reed instruments were first depicted by the ancient Egyptians some 3000 years BC (Joppig, 1981, p. 8; Simon, 2016). The bassoons predecessor is the instrument called Dulcian, whose origin has many hypotheses, however according to Joppig (1992) all of them can be refuted (p. 22). Dulcians that are considered to be the early form of the Basson are dated back to the 16th and 17th century (Voigt, 1975, p. 5). According to Joppig (1992) the first description of the *Fagott* (German word for Bassoon) comes from Michael Pretorius for the 16th century where the terms Dulcian and Bassoon are intermitted and are referred to as the same instrument (p. 22). The term *Basson* has been used as the name for the bassoon in France since 1613 (Reimann, 1956). A clear distinction between the dulcian and the bassoon, considering their constructional and nomenclatural history, began to emerge during the first half of the 20th century (Angerhöfer, 2016).

The hight of the Bassons popularity as a solo instrument was reached in the Baroque aera, and while it has lost on its popularity as a solo instrument in the Classical aera it remained an important instrument in orchestras (Joppig, 1985). Joppig (1985) continues by saying that technological advancements from the field of acoustics and the the inventions of equal temperament have further transformed the instrument at the beginning of the 19th century. In this century one Bassoon manufacturing family from Germany by the name of Heckel has built improved Bassoons whose popularity has led to the dominance of a Bassoon construction type we today call the “German model” that is still the most popular today (Angerhöfer, 2016). Next to the German model the other popular model is the “French model” (Fig. 1), however the German model remains the dominant one (Campbell et al., 2004, p. 98).

The bassoon family comprises only two instruments: the bassoon, with a range spanning from B♭1 to E5, and the contrabassoon (or double bassoon), which has a range from B♭0 to C♯4. Due to its substantial size and high cost, the contrabassoon is primarily used in orchestral settings (Campbell et al., 2004, p. 98). Since the German model is more commonly used today, it serves as the reference point for general statements regarding the construction of the modern bassoon (Campbell et al., 2004; Waterhouse, 2001; Baines, 1962). The bassoon is constructed in five distinct parts (Montagu, 2007, p. 83). The first is the crook (or bocal), a curved metal tube with a diameter of about 4 mm at its smaller end (Baines, 1962, p. 151). The second is the wing joint, named for its flattened shape, which resembles a bird's wing. The third part is the butt joint (or boot), made of two conical sections joined at the base by a U-shaped metal piece and covered by a protective metal cap. This section is equipped with a hand support called a crutch. The fourth part is the long joint (or bass joint), which is positioned alongside the wing joint. Finally, the fifth part is the bell, which has an open end with a diameter of approximately 4 cm and often includes a bulge midway along its length for added strength. The bassoon can be supported either by a sling or an adjustable spike attached near its base. (Campbell et al., 2004, p. 98)

Figure 1. This figure is showing Modern bassoons: (a) shows German system, made by Wilhelm Heckel, Biebrich; (b) shows the French system, made by Buffet-Crampon, Paris (private collection) (Waterhouse, 2001).

2.2 The Bassoon Double Reed

The reeds are attached to the bocal, which fits into a socket located at the top of the wing joint (Bucur, 2019, p. 49). The double reed of the bassoon is crafted from a single piece of cane shaped into a tube and secured with wire (Bate & Bruges, 2001). The two flexible cane strips are bound together at one end around a narrow tube called the staple, which fits into the instrument's playing end (Campbell et al., 2004, p. 53).

The sound produced by wind instruments comes from the movement of air particles inside the instrument, which are set in motion by the reed (Lewcock et al., 2001). When the double reed is blown, the elliptical gap between the ends of the blades starts to open and close, which gives bursts of energy to the air column (Bate & Burges, 2001). In response to pressure changes both inside the player's mouth and within the reed itself caused by the continual movement of the two reed blades starts the sound (Polychronopoulos et al., 2021). The reed sits partly in the player's mouth and vibrates when air is blown through the small gap between the two reed strips (Campbell et al., 2004, p. 53). The player's breath creates a pressure that forces air through the instrument, causing the reed to vibrate and produce sound, called blowing pressure (Vergez, 2003).

The reed and the air inside the instrument must work together to create stable, musical sounds, during which process the reed acts like a valve, responding to pressure changes in the player's mouth and controlling the airflow into the instrument, creating bursts of air that help maintain the vibrations of the air inside the instrument (Lewcock et al., 2001). By blowing into the instrument, the player destabilizes the single or double reed, while the instrument's acoustic response forms a feedback loop that influences the reed's vibration (Bucur, 2019). According to Vergez et al. (2003), in double-reed instruments, the pressure at the reed and the pressure inside the instrument are linked by a complex, nonlinear relationship, unlike simpler reed instruments.

Campbell et al. (2004) explain that the player's blowing causes the reed to settle into a vibration pattern where the gap between the reeds opens and closes at a frequency that matches one of the natural frequencies of the air column inside the instrument, a a pattern of vibration that shapes the strength and tone of the note produced (p. 53).

Voigt (1975) observed that the formation of formants in bassoons, dulcians, and other double-reed instruments is linked to the periodic air pulses at the location of the reed. A formant is a specific resonant frequency that helps shape the tone or timbre of the sound produced (Taylor, 2001). According to Voigt (1975), photographs of reed vibrations and sound patterns show that these formants come from the reed's own vibrations rather than from the way the reed's sound interacts with the instrument's tube.

Double reeds are classified as inward-striking reeds, meaning that when blowing pressure increases, the gap for airflow narrows, and excessive pressure can close the reed entirely, stopping the sound (Campbell et al., 2004, p. 54). According to Bucur (2019) the feedback loop caused by blowing, which influences the continual closing and opening of the reed many times per second, requires the reeds to be flexible enough (p. 167). On the other hand, the reed must be hard enough to resist high pressure exerted by the players blowing (Fletcher & Rossing, 2012, p. 495). Furthermore, a variety of factors can be manipulated to affect the acoustical properties of the reed, including wire placement and thickness, tube formation and wrapping, blade shape and length, profile and tip thickness, cane gouge, density, and selection, as well as the environment in which the reed is played (Gambill, 2024; Kopp, 2013).

Therefore, the chosen materials and design for the double reed are of high relevance to the quality of sound production.

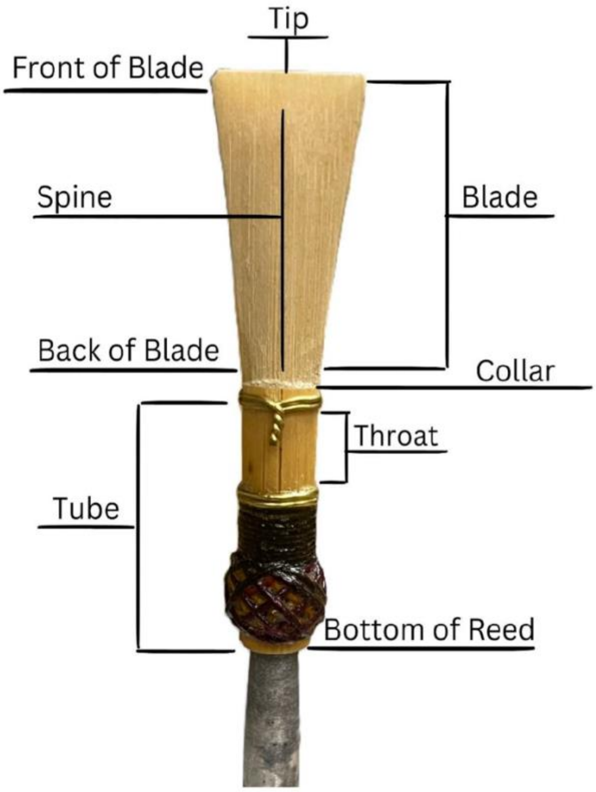

Figure 2. This figure is showing a bassoon double reed with all its separate parts (Gambill, 2024).

2.2.1 Double Reeds from Arundo Donax

Bassoon reeds of the highest quality are made from *arundo donax*, a bamboo-like plant often called cane (Kawasaki et al., 2016). *Arundo donax* is cultivated mainly in southern France, its quality varies with soil, climate, and harvest timing, much like wine (Campbell et al., 2004, p. 105). According to Kopp (2003), „one fundamental requirement of a bassoon reed is that it have both a tube and blades "(p. 52) - which is surprisingly hard to find among naturally occurring materials that are also easily workable. The reed consists of three concentric layers: (1) a hard, waxy epidermis with outer cortical cells, (2) a thick band of sclerified fibers, and (3) a dense inner cortex

(Kolesik et al., 1998). The first and the second one is hard enough to make the mouthpiece structurally stable, however these first two layers must be scraped away at the beginning of the mouthpiece to free the inner cortex, the only layer flexible enough to resonate easily (Kopp 2003).

According to Bocur (2019), to successfully mimic cane, new materials must match cane's defined physical parameters—density, elasticity, damping, anisotropy, moisture content—within their optimal ranges, be non-toxic, and satisfy musicians' tonal expectations. Density, defined in physics as the mass contained in a unit volume, can also be expressed as relative density, which compares the material's density to that of water; for cane (*arundo donax*), the relative density ranges approximately between 0.40 and 0.80 (Kollmann & Cote, 1984). There is no good or bad density for reeds, however, is one more adapted the taste of the player or a specific instrument (Bucur, 2019). For example, the German bassoon's preferred cane density is 0.60 while that of the French bassoon is 0.53 (Heinrich, 1991). The quality of manufactured reeds is unpredictable due to high density variability, however there are ways to measure density scientifically (Heinrich, 1991; Lacy, 2001), which is the key parameter to measure.

A high young's moduli, commonly referred to as stiffness, plays a crucial role in the cane reed's good acoustical performance (Lawton, 1998; Spatz et al., 1997; Kopp, 2003). Furthermore, the cane's fibers rotate in a specific way so that it has a material strength in all three planes, resulting in equal and stable vibration in all directions, contrary to wood, which because of its fibers has strength on only one plane (Kopp, 2003). As a result, the vibration of the sound produced by a wooden reed would be unstable, or no sound would come out at all.

The third important trait of the cane is that it damps quickly, that is attributed to cane's anatomical structure and is essential since reeds of musical instruments require quick damping at very high frequencies (Speck & Spatz, 2004). Quick damping allows the player to end the notes when he wishes and isn't a problem since the player generates vibration by continuously blowing (Kopp, 2003).

The water absorption cane is one of its crucial attributes, since the reed is not expected to vibrate until it has been thoroughly soaked (Ewell, 2017; Bocur, 2019, p. 185; Weissenborn & Saenger, 1941). In short, soaking will lessen its stiffness (or as a physicist would say: its modulus of elasticity drops exponentially) and lower the vibrating frequency (Kopp, 2003), as well as its stiffness (Bocur, 2019, p. 185). The reed's dimensions also expand when soaked and even result in the mouthpiece's change in form:

„When the bassoon reed is allowed to dry, the tip aperture will often become partly or fully closed. But hydrating (fully soaking) the reed causes the blades to swell in thickness, increasing the tension and restoring the tip aperture to the correct degree of openness, a critical requirement for correct vibration of the reed. "(Kopp 2003, p. 52)

In a clarinet reed, swelling occurs at 16% in the radial direction, 7.5% in the tangential direction, and 4.5% in the longitudinal direction, with free water comprising 3.75% of the mass when saturated (Casadonte, 1995, p. 244-246). In contrast, swelling is less significant in bassoon reeds, which are gouged thinner, have a higher proportion of sclerified cells, and adsorb less water.

Bassoon reeds change as they age, both chemically and physically (Casadonte, 1995). A key factor is the loss of hemicellulose (AMGX), which makes the reed less able to absorb water and softer over time—this is part of the "breaking-in" process. Saliva and bacteria can also affect the reed, adding weight, making it more brittle, and reducing its ability to vibrate effectively. While lignin, a water-repelling part of the reed, stays intact, it can cause the reed to gradually lose its shape and flexibility due to repeated swelling and drying. Over time, the reed's tip aperture (opening) narrows, making it harder to control and requiring adjustments to the wires. Solutions to slow down reed aging include antibacterial rinses, polymer treatments, or processes to make the cane more durable and resistant to wear. It is hard to measure it exactly, but the typical lifespan of a bassoon reed is around one month (Arbiter 2020, p. 33-34).

2.2.2 Traditional Double Reed Manufacturing

The reed goes through 3 main development stages until it embodies its final form and can be used to sound the bassoon: (1) becoming a reed blank, (2) thinning by the manufacturer and (3) adjustments by the player (Bucur, 2019). *"From about 1975 different polymers were invented as substitutes for cane"* (Bucur, 2019, p. 564), however most bassoon reeds are from *Arundo donax,* therefore it's manufacturing will be discussed first.

In the first large phase of becoming a reed blank, cane is cut into a piece of tube 12 to 14 cm long and about 2.5 cm in diameter**,** then split vertically into three or four pieces to form blanks for reed making (Waterhouse, 2001). In the following phase, the cane blanks are gradually thinned down by the manufacturer. Roughly half of the outer surface is thinned toward the tip, which serves as the vibrating element (Campbell et al., 2004, p. 105). The blanks are then folded to half their length, cut to size using a metal shaper, formed on a mandrel, and bound with three wires and thread (Waterhouse, 2001).

Each reed maker uses their own unique techniques for further thinning, often treating these methods as closely guarded secrets (Campbell et al., 2004, p. 105). The shape of the thinned area is critical to defining the reed’s playing characteristics. Final thinning of the reed blades may be done with a profiling machine, or manually with a file and scraping knife (Waterhouse 2001). The blade tip, which is approximately 0.1 mm thick, is very fragile and plays a crucial role in the tone and response of the instrument.

Due to the natural variability of cane, players often adjust reeds to suit their preferences (Campbell et al., 2004, p. 106). Manual tools, such as gougers, splitter knives, and mandrels, are simple but essential for shaping and thinning reeds (Bucur, 2019, p. 563). Modern equipment allows skilled musicians to craft reeds with exceptional consistency, but many still prefer handmade reeds for professional use, favoring the ability to scrape reeds with a sharp knife or razor to achieve the desired strength and tonal quality (Campbell et al., 2004, p. 106). It is important to note that new reeds tend to feel hard but soften with use, requiring careful adjustments to achieve optimal performance characteristics. Campbell et al. (2004) also say that the amount of thinning in specific areas is crucial for balancing the reed’s strength and flexibility (p. 106).

According to Heinrich (1991), bassoon players encounter three challenges when they are adjusting their reeds: handling the raw material, the structural architecture of the cane reed and connecting the parts of the reed with each other and the instrument (p. 610). While the last two can be mastered intuitively requiring patience and experience, handling the raw material can be a real mystery, since reeds can sound extremely different ranging from extraordinary to unplayable (Heinrich, 1991, p. 611). Therefore, the quality of the raw material is crucial for crafting a high-quality reed (Bucur, 2019, p. 563).

2.2.3 Double Reed Manufacturing Using Alternative Materials

Interest in using new materials for reeds is relatively recent compared to the long history of wind instruments (Bucur, 2019, p. 574). Synthetic materials offer several advantages, including better manufacturing control, provided their acoustic and mechanical properties are suitable. One group of materials, polypropylene, can be engineered with unidirectional or bidirectional properties to match the stiffness and density of moist cane. These reeds benefit from advanced fabrication technologies, such as computer-controlled precision cutting, which ensure high-quality production. Double reeds are manufactured in two halves and bonded using digital precision systems.

According to Légère (n.d.), one of the most well-known synthetic reed manufacturers, Légère reeds are precision-crafted from a proprietary polymer using a 3-axis CNC (computer numerically controlled) cutting machine. CNC, or "computer numerical control," refers to a subtractive manufacturing process that uses computerized controls and machine tools to remove layers of material from a stock piece, known as the blank or workpiece, to create a custom-designed part (Mamadjanov et al., 2021). CNC was a technology developed in 1957, started gaining popularity in the 70s and gradually started to dominate the market (Dixit, 2022, p. 4). CNC machines offer high accuracy, repeatability, improved quality, reduced waste, efficiency in mass production and enables creating complex geometries that were not possible before (Negi, 2019, p. 2). The use of CNC manufacturing technology for the production of reeds is only made possible by Légère's use of their own unique polymer, that must be a material with far less variability than the material of the cane (Bucur, 2019, p. 575). One of the advantages of CNC that they operate automatically during the manufacturing and fabrication of parts and components (Negi et al., 2019, p. 3), which removes the need for a manual reed making professional from the process.

2.3 Additive Manufacturing

Essentially, Légère's CNC cutting machine uses subtractive manufacturing, since *"subtractive manufacturing includes all processes that generate a final product, or intermediate-stage product, through the removal of material."* (Watson & Taminger, 2018, p. 1318) The opposite of subtractive manufacturing is additive manufacturing. According to Watson and Taminger (2018), additive manufacturing encompasses all processes that create a final or intermediate product by layering feedstock onto a substrate. There are terms often used as synonyms to describe additive manufacturing technology, for example the terms "Stereolithography" (SL) and "3D Printing" (3DP) originally referred to specific technologies (Gibson, 2015, p. 8). The first commercially available SLA printer was patented in 1986 by Charles W. Hull, founder of 3D Systems Inc., with the goal of enabling rapid prototyping of plastic parts (Schmidleithner & Kalaskar, 2018), while 3DP was developed by MIT researchers using an inkjet-based process (Gibson et al., 2021). Both terms draw from 2D processes like lithography and printing, extending them into three dimensions (Gibson, 2015, p. 8). Over time, "3D Printing" has gained widespread usage, driven by media attention, and is now the most recognized term for additive manufacturing among the general public (Gokhare et al., 2017). This is also due to the familiarity of traditional printing, therefore the concept of "printing" 3D objects resonates with most people (Gibson, 2015, p. 8).

As already mentioned, The first 3D printer was developed by Charles W. Hull, it utilized stereolithography and was commercialized in the mid-1980s (McCausland, 2020). This process involved using a UV laser to trace the desired object onto the surface of a vat filled with UV-sensitive photopolymer (Wohlers & Gornet, 2014, p. 1). Modern additive manufacturing has since introduced a wide range of 3D printing techniques, broadly categorized into two main types: continuous inkjet and drop-on-demand inkjet (Bucur, 2019, p. 597). Continuous inkjet technology ejects a constant stream of droplets from the printhead, while drop-on-demand technology releases droplets only when needed (Castrejon-Pita, 2013).

2.3.1 The process of Additive Manufacturing

Bucur (2019) describe additive manufacturing as a process that builds objects layer by layer based on CAD data, with model quality and accuracy influenced by layer thickness, machine capabilities, material properties, and post-processing requirements (p. 593). Additive manufacturing progresses from CAD design to a finished part, serving various purposes from basic visualization models to detailed engineering, with rough parts produced early and later refined through post-processing like sanding or painting, excelling in creating complex shapes without tooling (Wa et al., 2015, p. 4).

According to Gibson et al. (2015) additive manufacturing (AM) processes typically involve eight key steps to some extent (Fig. 3) (p. 4). The first step is creating a virtual description of the product using computer-aided design (CAD) modeling, producing a 3D solid or surface representation through techniques like laser and optical scanning. Next, the CAD data is converted into an STL (Stereo Lithography) file format, which provides a detailed listing of the XYZ coordinates of the vertices and normals of the triangles that define the 3D object. This file forms the basis for calculating the model's slices. Gibson et al. (2015) continue by saying that the third step involves transferring this data to the AM machine, where the size, position, and orientation of the object are verified. In the fourth step, the machine is set up with the appropriate parameters, including material properties and layer thickness (p. 5). The fifth step is the actual building of the parts, which happens automatically once the machine is set up. After printing is complete, the sixth step involves carefully removing the parts from the printer, ensuring that operating temperatures are safe for handling. In the seventh step, post-processing is carried out, which may include cleaning, sanding, or other finishing touches. Finally, in the eighth step, the parts are ready for their intended application. However, before use, certain conditions must be met, such as achieving an acceptable surface texture or applying paint or other coatings as needed.

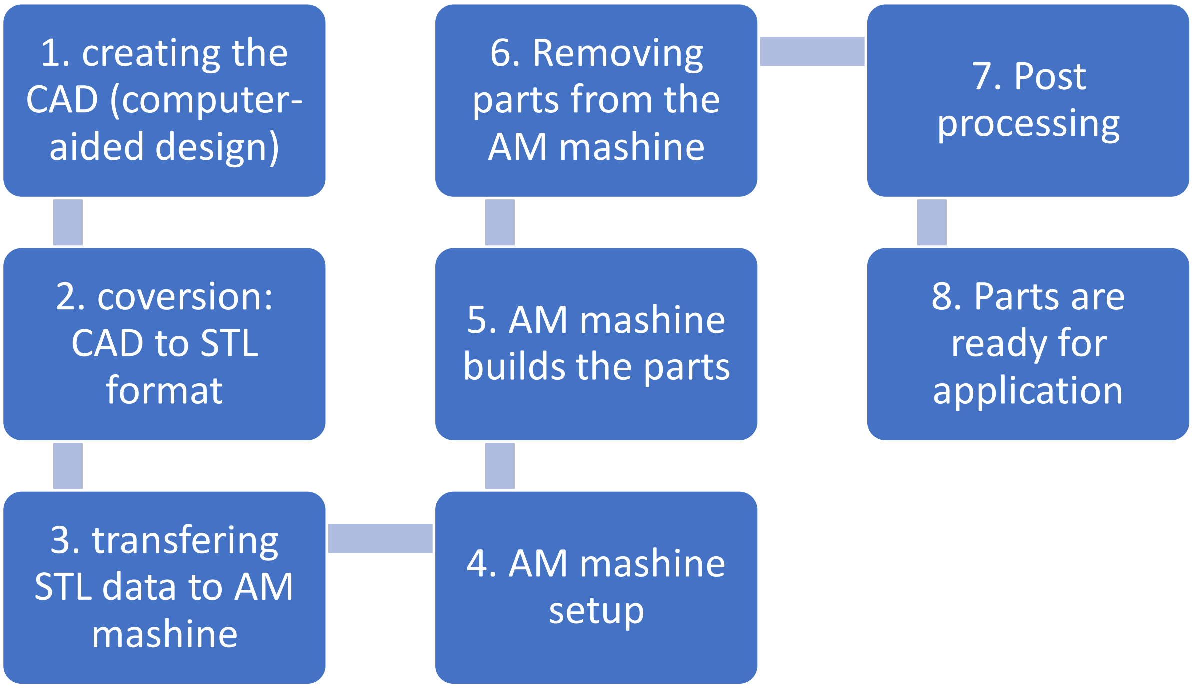

Figure 3. This figure shows the 8 key steps of the Additive Manufacturing process according to Gibson (2015).

Additive manufacturing processes are classified into seven categories depending on their way of processing: liquid vat photo-polymerization, material jetting, binder jetting, material extrusion, powder bed fusion, sheet lamination, direct energy deposition (Bourell et al., 2017, p. 659-660). Choosing the right manufacturing technology depends on factors like the machine's resolution, material properties, process compatibility, design feasibility, and simulations to ensure mechanical criteria such as stress limits, failure strength, and bending radius are met (Bucur, 2019, p. 594).

2.3.2 The Use of Additive Manufacturing in Wind Instruments

To create an overview, Damodaran et al. (2021) have gathered several studies that used additive manufacturing to produce wind instruments, although the number of these studies is low due to AM technology being overlooked in the field of music instrument manufacturing (p. 2). None of the studies have attempted to create a double reed for a bassoon or any reed, double or single, at all. Other literature search methods indicate that such studies are still in the making and are yet to be published. None the less, other literature on the use of additive manufacturing in wind instruments can serve as a point of departure for identifying what AM process and materials should be used. Furthermore, they should help create a working CAD design for a successful double reed production.

2.3.2.1 Manufacturing Wind instruments with AM: Geometry

Compared to musical instruments like percussion instruments where sound production is made by a membrane stretched over a closed cavity, the sound production of wind instruments mostly relies on the geometry of the instrument (Damodaran, 2021, p. 2). For example, the length of the tube is proportional to the pitch of the instrument, and the proportions used for an AM design will play an important role in pitch, playability, and sound quality. Lorenzoni et al. (2013) say that the advantage of 3D printing technologies for manufacturing saxophone mouthpieces lays in allowing the production complex inside geometries that are difficult to achieve with machining (p. 419). In their study they created such inside geometries to influence the flow structure and turbulence levels inside the mouthpiece that influence the playability and sound quality. They were able to create mouthpieces that can be tailored for the individual sound requirements of musicians.

One of the main advantages of using AM is the possibility to create more complex geometries (Gibson et al., 2015, p. 11-12). Additive manufacturing (AM) simplifies creating 3D objects by breaking them down into thin 2D layers stacked on top of each other. This method avoids the need for complex surface connections in 3D, as layers are joined simply by being close together. CNC machining, on the other hand, must shape surfaces directly in 3D space. While straightforward shapes like cylinders or cubes are relatively easy for CNC machines to handle, more complex, freeform designs require precise tool movements and frequent changes in orientation, making them much harder to create. Even with advanced 5-axis CNC systems, features like sharp corners, undercuts, or enclosed spaces can be very tricky and often require repositioning the part multiple times.

Dubrovski et al. (2012) have built saxophone mouthpieces (reed not included) with AM and tested them with professional players (p. 4). They said that additive manufacturing offers unparalleled flexibility to replicate complex geometries with diverse materials, that allows tesiting a wide range of saxophone mouthpieces within just a few weeks. Dubrovski et al. (2012) were able to implement small adjustments to the internal chamber to explore their effects on acoustic performance and playability in ways that cannot be fabricated with other manufacturing methods (p. 5).

2.3.2.2 Manufacturing Wind instruments with AM: Material

Besides the geometry, the material of the instrument or reed will also have a large impact on product quality. Generally, a quality instrument should resist low-level external impact and is dimensionally stable because change in the structure will influence sound quality (Damodaran, 2021, p. 2). In the case of the reed, the reed should be hard enough to resist the blowing pressure which is between 1.5 and 8 kPa (Fletcher & Rossing, 2012, p. 495).

The material of the instrument and its mouthpiece plays an important role in how it transmits, reflects or absorbs sound waves. (Spanou, 2019, p. 25) In the case of wind instruments hardness (resistance to abrasion) and stiffness (elasticity of the material) impact the sound the most. Mouthpieces are the *"part of a wind instrument which is placed in or against a player's mouth, and which, together with the lips or a cane Reed, forms the sound generator"* (Bate, 2001). They have much influence on tuning, the tone and behavior of the instrument. For choosing the best material for mouthpieces the most important characteristics are stiffness and density, while damping factor also plays an important role (Spanou 2019, p. 26; Damodaran, 2021, p. 2). Density and stiffness are related to sound frequency, while the damping factor will determine how dull (opposite of bright or edgy) the sound will be. For example, using thermoplastics like ABS (acrylonitrile butadiene styrene) that respond to varying temperatures and noticeably change their stiffness leads to inconsistencies in the sound of the instrument (Spanou, 2019, p. 26). Their density is also lower compared to other materials, as a result they are lighter and produce higher frequencies. However, there is a possibility to combine glass fibers or other substances with ABS to change their properties.

The large number of materials and their combination that can be used in AM technology poses a significant challenge in choosing the right one, however if at least the broad type of material is determined, its selection will instantly narrow down what process can be used (Bourell et al., 2017, p. 660). Bourell et al. (2017) collected all broad material types used in AM production. For example, *"semicrystalline polymers typically soften over a very small temperature range with a dramatic change in* *viscosity"* (p. 660). They continue by saying that the behavior of semicrystalline polymers is useful for the use of powder bed fusion of plastics AM method, however the polymer flow characteristics are difficult to control using a material extrusion AM method.

One possible way to select the right material would be to inspect the polymers that were invented from 1975 as a substitute for cane and cross reference the to the available materials available in AM manufacturing based on the physical attributes (Bucur, 2019, p. 564). For example, according to Bucur (2019), polypropylene's properties seem to match the properties of *Arundo donax* especially well (p. 574-575). According to Bourell et al. (2017), polypropylene can only be processed by the AM method of powder bed fusion (p. 660). In this case, the researcher path is quite forward. Unfortunately, not all AM methods are always available for researchers, so they often must reverse the process of material selection. For example, if the only available AM machine is using a material extrusion method (like in this study), only materials compatible with this AM method can be used.

Another possible way for selecting the right material is to rely strictly on the measurement of physical attributes. This requires the knowledge of necessary physical attributes of cane and the physical attributes of available AM materials. Bourell et al. (2017) surveyed the properties of AM materials including strength, stiffness, ductility, toughness, fatigue, optical properties and electrical properties (p. 675). The authors also propose the development of a process-specific additive manufacturing index to guide materials selection for AM.

The synthetic reed manufacturer Légére explain their manufacturing process in their page site *"Why they work"* the following way: *"Cane is a unique material. It has low density yet is longitudinally very stiff. Matching these properties in a synthetic material* *is difficult but is essential in creating a good reed"* (Légére Reeds, n.d.). Based on our knowledge of *Arundo donax's* properties discussed earlier in this section, the most important factors for replicating the attributes of unique material of *Arundo donax* with AM technology: (I) one should consider it's three separate layers and how they behave and have different functions; (II) The cane has moderate density, high thickness, and quick damping that should be replicated; (III) The cane's fibers rotate, that has an important effect on stability and equal vibration in all directions and lastly, (IV) the cane changes density, thickness, shape and expands in size when soaked (Kopp 2003). Theoretically, since both *Arundo donax's* and physical attributes of available AM materials are known we can find the most matching material or attempt to experiment in mixing the most suitable materials for the AM production a double reed. However, there are some general challenges typical for AM processes. Materials play a crucial role in additive manufacturing (AM), especially for engineered structural applications (Bourell et al., 2017, p. 675). To succeed in AM processes, materials must be suitable for feedstock preparation, compatible with the specific AM machine, and possess the necessary properties for practical use. There are materials particularly amenable to AM processing including polymers (amorphous and semicrystalline thermoplastics, and thermosets), metals, ceramics and composites. The importance of layer binding in AM is critical, since issues such as porosity, binding defects, and microstructural inconsistencies can lead to flaws in finished parts.

2.3.3 AM Processes Used for Manufacturing Wind Instruments

According to Damodaran (2021), the key applications of additive manufacturing (AM) in the context of musical wind instruments fall into five main categories: (i) restoration and repair of historic instruments, (ii) research and development, (iii) education and training, (iv) personalization, and (v) innovation (p. 7). AM technologies used for wind instrument production are systematically categorized in Figure 4. Zoran (2011) says that While 3D printing technology still faces challenges—such as limited resolution, material quality, and stability—that restrict its use for manufacturing rather than just prototyping, it's easy to see its potential in revolutionizing acoustic instrument design as the technology matures (p. 386). Digital design and fabrication tools could unlock shapes and modifications that are currently impossible to achieve through traditional methods. Whether enhancing existing designs, like adding an extra valve to a trumpet, or inventing entirely new instruments, digital fabrication holds immense promise for musical instrument innovation.

From a wider perspective, advancements in additive manufacturing are steering factories toward customized production, reviving the craftsmanship era when artisans created unique items tailored to individual customers (Negi et al., 2019, p. 13). Dixit (2022) says that this could revive the domestic production model, now enhanced with advanced technologies and according to it wouldn't be far stretched to expect the factory model become obsolete (p. 9). in the case of traditional reed making, technology could rather empower hand-made production of instruments, including bassoon reed production, rather than contribute to them being replaced by companies using mass production.

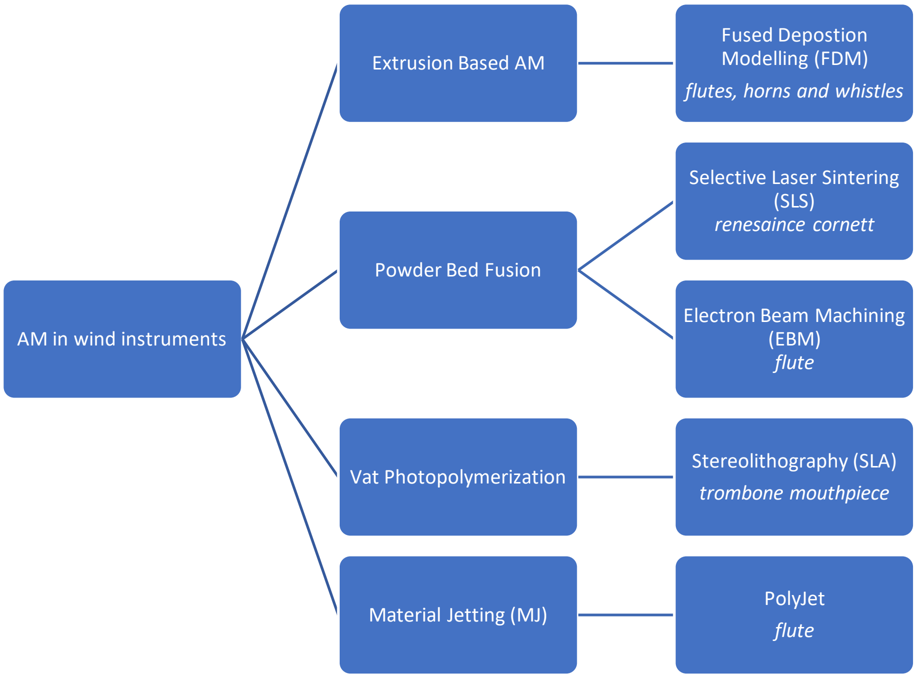

Figure 4. This figure is showing AM processing technologies that were used for creating wind instruments grouped in their main and subcategories (Damoradan, 2021; Bucur, 2019).

2.3.3.1 Extrusion Based AM Technology: Fused Deposition Modelling (FDM)

Extrusion-based technology is currently the most widely used AM method in the market (Gibson et al., 2015, p. 147). While various techniques can create the extrusion, the most common approach involves using heat to melt the material in a compact, portable chamber. A tractor-feed mechanism generates the necessary pressure to push the molten material through the system for extrusion.

The most widely used extrusion-based AM technology is fused deposition modelling (FDM), developed and manufactured by Stratasys, USA (Gibson et al., 2015, p. 160). Fused deposition modelling (FDM), an extrusion-based AM technology, was mostly used for creating musical instruments like classical flutes, horns, and whistles (Damodaran, 2021, p. 3). The simplicity and affordability of FDM equipment, and availability of a high number of materials and their combinations, makes it a popular option for creating research prototypes and functional end parts. In FDM *"a thermoplastic wire material is heated (resistance heating) and the semi-molten material is deposited layer by layer via nozzle on a platform as per CAD model"* (Damodaran, 2021, p. 3).

Common materials used to produce wind instruments with FDM are PLA (Polylactic Acid) and ABS (Acrylonitrile Butadiene Styrene), both being considered an industry standard in FDM production (Marin et al., 2019, p. 243). Zoran (2011) reported on some issues when building all the parts of a fully modelled flute with FDM using the material ABS (p. 382). The FDM printing process in his study resulted in relatively rough surfaces on the holes and pads, causing air leakage issues. Which is a serious defect, since wind instruments demand that components to be airtight otherwise air punches out form the instrument (Damodaran, 2021, p. 5). Zoran (2011) also reported that ABS rings were printed to reinforce the flute edges and prevent cracking between layers—a common challenge associated with FDM printing (p. 383).

2.3.3.2 Powder Bed Fusion AM Technologies

The second large group of AM process used for the manufacturing of musical wind instruments is powder bed fusion (Damodaran, 2021, p. 5). Powder bed fusion is an additive manufacturing process where thermal energy, supplied by a laser or electron beam, selectively fuses specific areas of a powder bed. Techniques such as Selective Laser Sintering (SLS) and Electron Beam Machining (EBM) fall under this category.

2.3.3.2.1 Powder Bed Fusion AM Technology: Selective Laser Sintering (SLS)

Savan and Sivian (2014) say that the synthetic material that appears most suitable for wind instruments is SLS nylon, and chose therefore Selective Laser Sintering (SLS) as their AM method This material offers several advantages, including a density of 0.93g/cm³, which is comparable to boxwood (0.95g/cm³), precision up to a tenth of a millimeter, and heat resistance up to 80°C while maintaining strength and flexibility (p. 542). However, SLS nylon has a porous and rough texture, which necessitates additional finishing to seal the bore and ensure the instrument feels comfortable to hold.

2.3.3.2.2 Powder Bed Fusion AM Technology: Electron Beam Machining (EBM)

The second powder bed fusion technique mentioned earlier, Electron Beam Machining (EBM) has been used by Kolomiets et al. (2021) for printing a titanium flute (p. 3). Their choice was primarily based on EBM's ability to produce highly dense materials, which is expected to enhance acoustic properties. The use of additive manufacturing (AM) for a titanium flute has minimized material usage while improving its aesthetics (Kolomiets et al., 2021, p. 15-16). Titanium-AM demonstrates innovation through its durable, lightweight, and customizable designs, along with optimized wall thickness to achieve desired acoustic qualities. It was concluded that the sound produced by the titanium-AM flute is "richer" compared to a commercially available Yamaha polymer flute.

2.3.3.3 Vat Photopolymerization AM Technology: Stereolithography (SLA)

The third large group of AM process used for the manufacturing of musical wind instruments is vat photopolymerization (Damodaran, 2021, p. 6). Photopolymerization processes use liquid resins, or photopolymers, that harden when exposed to radiation, usually in the UV (ultraviolet) light range, though some systems work with visible light too (Gibson et al., 2015, p. 63). When these materials are hit with radiation, they go through a chemical change and solidify. This process, known as photopolymerization, is a complex reaction involving multiple chemical components.

Stereolithography (SLA) was the first vat photopolymerization process (Gibson et al., 2015, p. 63). Bacciaglia et al. (2020) have created mouthpieces for trombones with SLA as well as FDM processes and systematically evaluated them alongside traditional mouthpieces (p. 583). When comparing traditional metal mouthpieces to those made using FDM and SLA techniques, their evaluation showed that SLA-printed mouthpieces offered the best design results. They also noted that Additive manufacturing (AM) allows for high customization and offers a cost-effective solution for small production runs. With precise design and material choices, SLA technology can produce mouthpieces with a sound quality similar to commercial ones. On the other hand, the porous structure of FDM components does not deliver the same sound quality in tests.

2.3.3.4 Material Jetting (MJ) AM Technology: PolyJet

Damodaran et al. (2021) list material jetting as last of the four main groups of AM processes used for the manufacturing of musical wind instruments (p. 6). Material jetting (MJ) involves dispensing the entire part material from a print head (Gibson et al., 2015, p. 175). A PolyJet machine uses an inkjet head with hundreds of nozzles that move along the x-axis, ejecting tiny droplets of photopolymer (Damodaran, 2021, p. 7). After each layer is deposited, a UV lamp quickly cures it, and the process repeats. The key advantage of this method is its ability to use multiple materials with different physical properties. The Material Jetting method could be interesting for the reproduction of cane, whose layers have very different physical attributes, so these might only be successfully replicated by combining multiple materials.

3. Method

Additive manufacturing (AM) is increasingly used to create wind instruments with unique designs and personalized features, benefiting both professional musicians and beginners with affordable options (Damoradan, 2021, p. 11). It also aids in restoring and conserving historical instruments by producing functional replicas using advanced CAD technologies. Additionally, AM enhances the understanding of sound production in wind instruments and serves as a valuable tool for music education. Overall, AM's role in wind instruments is growing rapidly, offering new opportunities for innovation and research. AM is also empowering small instrument manufacturers and players interested in experimentation and creation of new instruments as well as instrument customization that is becoming more and more easy and cost effective (Negi at al., 2019, p. 13.). The focal point of this thesis is the attempt to create a working bassoon double reed using AM technology. The main factors in choosing the methods of AM were to identify the smallest features the machine can handle, to pick the right material for the process, and to make sure the design works for production (Bucur, 2019, p.

594). Picking the right material and what AM method should be used are strongly interdependent (Bourell et al., 2017, p. 675).

3.1 Choosing the AM method: Fused Deposition Modelling (FDM)

The AM method was picked based on availability and cost primarily. The available AM machine was the Original Prusa MK4S 3D Printer manufactured by the company Prusa Research commercially avalible in Austria for just over 1000 EUR ("Original Prusa MK4S 3D Printer," n.d.). The Prusa MK4S utilizes fused deposition modeling (FDM), the most common type of 3D printing. In this process, a thermoplastic filament is heated to its melting point and then extruded layer by layer to form a three-dimensional object. The Prusa currently uses an open-source software called PrusaSlicer 2.8.1. that according to them is a "feature-rich, frequently updated tool that contains everything you need to export the perfect print files for your 3D printer" ("Original Prusa MK4S 3D Printer," n.d.). FDM technology has become a popular choice for developing prototypes and functional end-use parts in research due to its simplicity, affordability, and the availability of raw materials (Damodaran, 2021, p. 4).

A nozzle diameter of 0.25mm was used, with a vertical layer height of 0.10mm. These parameters influence printing precision, and their exact number was determined during a process of experimentation, since for example a larger nozzle diameter resulted in cracks and defects that rendered the mouthpiece unplayable. The chosen nozzle diameter and vertical layer height parameters also influence water absorption. Ayrilmis et al. (2019) found, that the water absorption of the 3D-printed samples increased as the printing layer thickness grew. They attributed this to the increase in empty spaces within the 3D-printed structure as layer thickness increases, allowing more water to be absorbed.

Time spent and the available budget play an important role in determining if a study will be conducted. Luckily, the finished product takes under an hour to print and uses around 1g of material, which at the time of writing equates to a material cost of under €0.05 – a great contributing factor why this AM method and material were chosen for this thesis (“Original Prusa MK4S 3D Printer,” n.d.).

3.2 The Double Reed design

For the 3D printed double-reed, a freely available STL (stereolithography) model was used (Samarqand, 2019). The model describes half of a bassoon reed, sliced laterally. Two copies of the reed may be printed and later tied or glued together (Fig. 5). “Tying” or “wrapping” is an integral part of traditional double-reed producing and it means the process of attaching a piece of cane to a staple or tube (Young Rennick, 2010, p. 25). A successful trying process results in a reed “blank,” and to complete the tying is considered the most significant challenge of young players. However, initial experimentation and prototyping with the STL model yielded better results when both halves of the model were combined before printing, and the model was then printed standing upright (Fig. 6). This resulted in the two cane halves being molded together during the printing process, which eliminated the need for tying. On the other hand, the two halves were completely molded together, which resulted in the reed not being able to vibrate when blown. This problem was solved by separating the two reed halves starting from tip aperture by cutting through where the two halves were molded. For a lack of terminology, we have named this process “cutting in” and have measured the length of “cutting in” in a distance (mm) starting from the tip aperture.

3.3 Material

The Original Prusa MK4S 3D Printer supports "PLA, PETG, Flex, PVA, PC, PP, CPE, PVB and when using the Original Prusa Enclosure with filtration add-on ABS, ASA, HIPS, PA" ("Original Prusa MK4S 3D Printer," n.d.). In the field of wind instrument making, Damodaran et al. (2021) say that FDM supports a variety of printing materials, with PLA (polylactic acid) and ABS (acrylonitrile butadiene styrene) being the most used, along with other additives (p. 5). In a study examining the acoustic properties of various materials for 3D printing string instruments, it was found that acoustical data initially suggest PLA as a favorable option for selecting materials for the 3D printing of string instruments (Zvoníček et al., 2023, p. 13). However, despite its popularity in entry-level 3D printing, PLA's poor mechanical strength makes it unsuitable for handling the tension exerted by strings on the instrument. Since the double reed should resist the blowing pressure up to 8 kPa, PLA is again expected to fail in handling the tension exerted by the players blowing (Fletcher & Rossing, 2012, p. 495).

Recent studies indicate that PET-G (glycol-modified polyethylene terephthalate) is a more suitable material, offering a balance between acoustic performance and mechanical durability (Zvoníček et al., 2023, p. 13). While advanced materials like carbon fiber-reinforced nylon provide superior strength and good acoustical properties, their higher cost—both in terms of material price and increased printing time—can make the process less feasible on a large scale. PET-G`s (glycol-modified polyethylene terephthalate) great elasticity and durability was confirmed by Ronca et al. (2022) as well.

Another differentiating factor between PLA and PET-G is water absorption, since the mouthpiece will be moisturized during playing. The water absorption of PLA and PET-G was compared by immersing them in *"saturated solutions of water with maritime salt and sugar together with a control sample immersed in distilled water"* (Moreno Nieto et al., 2021, p. 1). The conclusion was that PLA specimens showed weight reductions due to their organic nature and degradation through hydrolysis. Dissolving outer layers allowed fluid penetration, initially increasing weight until stabilization. This process revealed gaps or cavities inherent to additive manufacturing (AM). In comparison, PET-G specimens demonstrated significantly lower absorption rates, around 0.15%, and a weight variation of approximately 0.3%. Meanwhile, PLA specimens showed a more substantial average weight increase of 2.5%, despite literature suggesting absorption rates below 1%. The cane reed's ability to vibrate strongly depends on how thoroughly soaked it is (Kopp, 2003). However, PLA's relatively high variance and degree in absorption could produce an unwanted inconsistency in reed vibration (Moreno Nieto et al., 2021, p. 12). The improved stability of PET-G can be attributed to its higher degree of crystallinity, which enhances its resistance to fluid absorption.

Both PLA and PET-G exhibited signs of degradation, including color changes caused by hydrolysis, where dipolar water molecules disrupted the carbon-hydrogen bonds in the polymer (Moreno Nieto et al., 2021, p. 12). This effect was more pronounced in the PLA specimens. PETG specimens, on the other hand, turned transparent, likely due to changes in the polymer's crystallinity. Based on these findings, PETG emerges as a suitable material for applications involving liquid exposure, such as in the maritime and packaging industries, or creating a double reed. As a result, PET-G was chosen as the printing material over the more widespread PLA (polylactic acid) for this thesis.

3.4 Toxicity and environmental impact

The question of toxicity is of extremely high importance since the chosen material is placed directly in the mouth of the player, and environmental impacts shouldn't be neglected either. Belloncle et al. (2012) measured the biodegradation, toxicity and ecotoxicity of PET-G and its relative byproducts (p. 726). They found that PET-G was harmless in all the studied categories. Furthermore, PET-G is a recycled material, often derived from the packaging industry, that not only demonstrates excellent processability and strong resistance to corrosion and wear but also contributes to a positive environmental impact by reducing waste through its reuse in additive manufacturing, with some brands even offering PETG sourced from previously printed parts or other industrial applications (Moreno Nieto et al., 2021, p. 3).

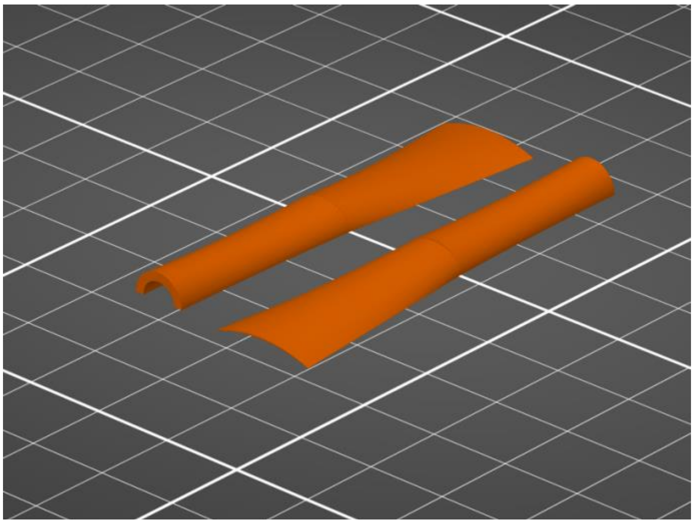

Figure 4. is showing the CAD virtual 3D model of reeds that are designed to be printed separately designed for this study.

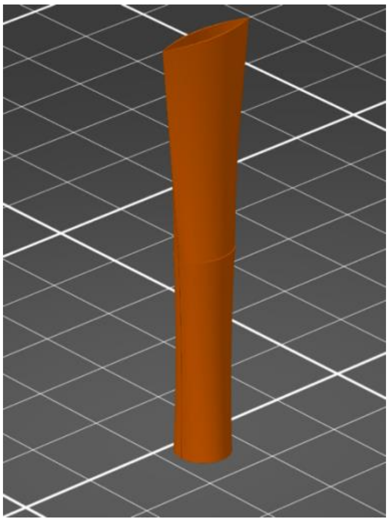

Figure 5. is showing the CAD virtual 3D model of reeds that are designed to be printed separately, standing upright designed for this study.

4. Testing the 3D printed Double-reed

The built double-reed was evaluated with the help of one professional bassoon player Szabolcs Szőke (from now on referred to as the player), who plays First Bassoon at Tonkünstler Orchestra from Vienna. In our semi-structured interview, we have evaluated playability, sound quality and design, while leaving out factors like price, building speed, durability and sustainability. The experiment consists of 3 phases: evaluation by inspecting the reed, reed's compatibility with the instrument, and reed's sound production.

The produced sounds by the player were recorded using a Zoom H5 Fourtrack Portable Recorder Earplug. The players cane reed he used at that time was recorded alongside the synthetic reed by playing the same long sustained notes on both reeds. Once the played notes were converted into digital form through recording, the signal can be analyzed using a mathematical method called Fourier analysis, which states that any periodic variation can be expressed as the sum of simple sine waves at multiples of the fundamental frequency, each with its own amplitude and phase (Taylor & Campbell, 2001). A Fourier analysis type relevant for the analysis in this thesis, the Discrete Fourier Transform (DFT) samples discrete time positions of the input signal and truncates the Fourier series after a set number of terms, approximating the continuous function when the sampling is dense (Fineberg, 2000). Fast Fourier Transforms (FFTs) are efficient algorithms that calculate DFTs by breaking computations into smaller parts, significantly reducing the required calculations (Hartman and Candy, 2014). With the help of FFT, a graphical display of signals from the two reeds in the amplitude (y-axis) and frequency domain (x-axis), as seen in similar studies, was created, allowing an objective comparison of the sound produced by the two reeds seen in similar studies comparing bassoon reeds and other woodwind mouthpieces (Gambill, 2024; Zoran, 2011).

4.1. Testing Phase 1: Evaluation by Inspecting the Reed

In Phase 1 the player was asked to evaluate the 3d printed double-reed only by inspecting it. Since most professional bassoonist, including the player, work intensively with carving their own cane reed, they can accurately predict how the shape and size our double reed will affect sound quality and playability – one competence professional bassoonists develop over time according to Heinrich (1991, p. 610). When asked about his competences, the player referenced his teachers, from whom he "learned everything" and never used any textbooks or other written materials for reed making.

The player was impressed with how similar the 3d printed double-reed looked compared to his other reeds (Fig. 7). There is a large database of cane reed measurements available on International Double Reed Society (IDRS), website collected with the cooperation of the editors of the Scrapes journal, that comprised of high-quality reeds with photos and exact measurements allowing for comparison and reproduction, which were also used in this thesis alongside the professional player's guidance and allowed the reed design to be as similar as possible to high-quality reeds (International Double Reed Society & Scrapes journal, n.d.). As seen on figure 5, the tip aperture length of the 3d printed double-reed is 12mm compared to the ideal width of 15,5-16mm in the case of a cane reed according to the player. On the IDRS website out of the 47 cane reeds listed most reeds had a width of 15,5-16mm, however there were canes used by professional bassoonists with the lowest width of 13.5 mm going up to 18.8 mm, this puts the synthetic reed below the lowest with 12 mm. After noticing the reed width, the player predicted that the reed "won't vibrate," and as a result no sound will be produced when blowing into it.

During the 3d printing of the reed, the printer failed to print the edges - the thinnest part of every reed entrance. This printing “mistake” was irrelevant according to the player, since a lot of players “cut these edges off” because these parts of the cane break easily and could destroy the mouthpiece if they do. Furthermore, the length of the 3d printed reed was 53mm, just 2mm shorter than the reed the player usually uses and wasn’t a significant difference according to the player. On the IDRS website the shortest reed was 51 mm and the longest 59.5 mm, which places the synthetic reed in the domain of less than average, which was around 55 mm (International Double Reed Society & Scrapes journal, n.d.).

The tip aperture (opening of the reed) seems a bit too wide (2,5mm) compared to his own that is 1,5 mm (Fig. 8). The tip aperture wasn’t measured IDRS website (International Double Reed Society & Scrapes journal, n.d.), only the placement of wires which determines the tip aperture size and form as well as the stability of the pitch (Gambill, 2024). The player predicted considerably greater opening width would make playability more difficult, since he will have more trouble in sustaining and controlling tones, and he will need more energy to blow the mouthpiece. This observation coincides with Kopp (2003) who says that tip aperture is critical for correct reed vibration and a too narrow tip aperture will result in no sound. Furthermore, an aperture that is too open makes the reed feel hard and tiring, with a harsh tone and difficulty in high notes, while one that is too narrow lacks resistance, feels soft, hinders forte passages, and risks closing during piano passages (Campbell et al., 2004). Because of the geometry of the mouthpiece was smaller than an average cane reed, he predicted it will produce a higher frequency, and the instrument will produce too sharp notes. Finally, the reed seemed a bit too thick according to the player, which is determined by the printing resolution.

Figure 7. This photo shows three different double reeds: the players cane reed he made himself and uses for concerts (left), our 3d printed reed (middle) and the a synthetic “medium-hard Bassoon reed” made by the company Légére owned by the player (right).

Figure 8. In this photo we can see the difference in opening width (tip aperture) between the player's 1,5mm wide cane double-reed (left) and our 2,5mm wide 3d printed double-reed (right).

4.2. Testing Phase 2: Reed's Compatibility with the Instrument

In Phase 2 the player was asked to insert the 3d printed double-reed into the bocal and describe how well it fits. Unfortunately, the diameter of the 3d printed double-reed was too small to fit on the players regular bocal. Therefore, the player had to use a smaller one he owns, however during inserting the 3d printed double-reed, it was damaged (Fig. 9). The solution was to tape the mouthpiece to the bocal to avoid air leakage and further fracturing (Fig. 10). This incident shows that the 3d print material isn't flexible enough to be fitted onto bigger bocals than its diameter. Furthermore, the fracture (Fig. 9) indicates the advantage of traditionally tied traditional manufacturing techniques where two cane parts are reinforced by tying them together at the end of the double reed and might explain why the company Légére reinforced their double reed with a metal (Fig. 7). Both manufacturing techniques created an increased resistance at the lowest part of the double-reed at the points where the 3d printed mouthpiece was fractured.

Figure 9. This figure shows the damage that was created when inserting the mouthpiece onto the bocal, and the air leakage that needed solving.

Figure 10. This figure shows our solution of taping the mouthpiece to the bocal to avoid air leakage and further fracturing.

4.3 Testing Phase 3: Reed's Sound Production

Phase 3 was the last and most important phase of testing where the player attempted to blow the mouthpiece to produce sound. Traditional manufacturing methods create the double reed out of two separate cane reeds and then tie them together. The company Légére manufactures them separately and then glues them together. During inspecting the Légére mouthpiece owned by the player it was noticed that the reeds weren't completely glued: starting from the mouthpiece entrance till the first 15mm in mouthpiece length the reeds weren't glued together (Fig. 11). From this it was deduced Légére's design choice had an important impact on playability and sound production.

When designing and 3d printing our prototype the mouthpiece was printed as one whole, and the payer was instructed to “cut in” starting from the entrance. For this experiment four different “cut in depths were determined:” 0mm, 5mm, 10mm and 15mm to see how they impact sound quality and playability. At 0mm “cut in depth” the player couldn’t produce any sound. When he attempted to cut in 5mm, the material fractured further than intended and the cut in depth was 10mm, however he managed to cut in exactly 10mm on the other side to balance it out. This incident also shows how the material of our 3D mouthpiece is unstable and post-manufacturing “cut in” currently isn’t the best approach to consistently create a playable 3D mouthpiece.

At 10mm “cut in depth” the player was able to produce sound with the mouthpiece. The player helped in selecting 4 different Bassoon registers with each register consisting of 3 notes: *First register* (B♭1, B1, C2), *Second register* (B♭2, B2, C3) *Third register* (B♭3, B3, C4) and *Fourth register* (B♭4, B4, C5). As a result, these 12 tones were recorded with the player’s regular cane mouthpiece made from Arundo Donax he currently uses for concerts and then recorded the same 12 tones with our 3D printed mouthpiece with a “cut in depth” of 10mm for our spectral analysis (Fig. 12). The player has successfully managed to accurately create the 15mm “cut in depth” and we have attempted to repeat the same process, however the mouthpiece broke during recording the *fourth register* beyond repair at 12,5mm from the mouthpiece entrance on both sides (Fig. 13). This was the final blow to our mouthpiece and shows how fragile our prototype is.

The most notable difference between the cane and 3D printed mouthpieces is their frequency difference. This resulted in the instrument being consistently too flat in the case of our 3D printed mouthpiece by almost a semitone, also reported by the player. This contradicts his prediction of the mouthpiece being too sharp. However, he realized that he was only able to push the mouthpiece onto the bocal by 3mm instead of the usual 10-13mm and thereby increased the total length of the mouthpiece. Such increase in mouthpiece length will alter the tube's proportions and result in a frequency change, confirmed both by the player and the findings of Damodaran (2021, p. 2).

The player was asked to evaluate playability in the case of the 10mm and 15mm "cut in lengths." He said that in case of the 10mm "cut in length" he had to apply a lot of pressure so he couldn't sustain tones for a long time. With 15mm "cut in length" the mouthpiece was easier to play on, was more playable and comfortable. He said that he could not use it for a concert though, since the mouthpiece is very stiff and as a result cannot be played on softly. He explained that this is because "the start of each note was very hard you could not start the note softly." In more musical terms, he could not produce the dynamic "piano," while "mezzo forte" and "forte" were easier to play. The mouthpiece being too stiff also made him feel uncomfortable while playing. There were some rare instances, were the played note jumped an octave, an occurrence the player could not explain.

When asked about tone quality, he said the tone quality wasn't flexible and the dynamic range he was able to produce very limited. According to him this was expected, since the mouthpiece opening was too wide (2,5mm) and the width of the mouthpiece was too narrow and therefore couldn't resonate properly. Consequently, these problems seem easier to solve with small design adjustments. Also, tone quality seemed less to do with "cut in length," so there was no notable difference between the 10mm and 15mm. Finally, when asked about damping and density, he said the tones ended faster than with his cane mouthpiece, and he said the 3D mouthpiece's damping was too quick. He also said that the cane reed seemed lighter indicating higher density in the case of our 3D printed mouthpiece.

Figure 11. In this figure our player is using one of his reed-shaping tools to show how his “medium-hard Bassoon reed” made by the company Légére isn’t glued completely. The distance between the entrance of the reed and the point where the two reeds were glued together is 15mm.

Figure 12. In this figure professional Bassoonist Szabolcs Szőke is recording tones on the 3D printed mouthpiece.

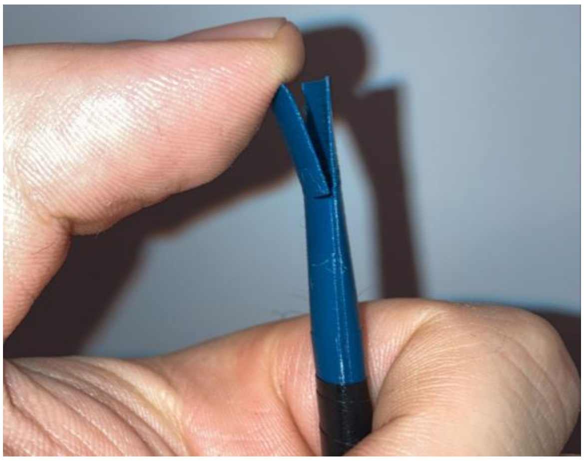

Figure 13. This figure shows broken 3D mouthpiece, that broke during recording the Fourth register of our 15mm “cut in depth” on both sides at 12,5mm from the mouthpiece entrance.

4.4. Spectral analysis

For the spectral analysis, excerpts of bassoon note recordings played across all ranges of the instrument (from C2 to C5) were taken, truncated to 2500 samples (corresponding to approx. 60ms), and normalized (Figs. 14-17). The Fast Fourier Transform breaks the complex sound of the played note into its partials – also known as fundamental frequency (the first partial), that is the first peak in the spectrum (Figs. 14-17), and overtones (Taylor and Campbell, 2001).

4.4.1. Spectral analysis: frequency

Partials are most relevant for sound perception when they are resolved, with the lowest 3–5 partials near the cochlear apex being resolvable because they dominate specific filters and produce quasi-sinusoidal outputs, making them critical to pitch perception (de Cheveigné, 2010), thereby when looking at the figures 10-13 comparing the first 5 partials will be the most relevant in comparing the sound of the 10 mm, 15 mm and cane reeds.

The first partial of the synthetic reed with 10mm cut in as well as 15mm show a spectral peak slightly lower than the conventional reed, due to the fact that the 3D printed reeds exhibited a fundamental frequency that was lower by approximately a semitone (Figs. 15-16). The most plausible explanation for this occurrence is related to instrument geometry, also verified by the player. Since it was only possible to insert the mouthpiece onto the bocal by 3mm, instead of the usual 10-13 mm, which in turn increased the length of the bassoon's tube, resulting in lower pitch because the pitch of a wind instrument is inversely proportional to the length of the air column (Carse, 2002). Another geometrical factor influencing pitch was the mouthpiece aperture width which was narrower (12mm compared to the typical 15.5–16mm) and larger tip aperture (2.5mm instead of 1.5mm) that may have altered the reed's ability to vibrate efficiently (Kopp, 2003), which resulted in a change of frequency- an effect the player also predicted. The natural elasticity of the used PET-G was found to be high enough for music instrument production, it might not be as flexible as cane which may also have caused a lower vibrating frequency (Ronca et al., 2022). Furthermore, the player noticed that he needed to apply more pressure to create a more stable sound which could be attributed to the tip aperture being too wide (Kopp, 2013), and the mouthpiece's higher resistance to the blowing pressure could have influenced the fundamental frequency of the sound as well.

During the testing it was established, that without "cutting in" and thereby separating the two reeds which were printed as one piece, the synthetic reed couldn't vibrate because it produced no sound when the player blew the mouthpiece. Thereby an inadequate "cutting in" technique or size might have caused a lower vibrating frequency. The spectral analysis reveals that the partials of the 10mm and 15mm cut in reed in the case of the tone C3 are nearly identical (Fig. 15). On the other side, in case of the C4 tone played by the player the spectral analysis shows a lower fundamental in case of the 15mm cut in compared to the 10mm cut in (Fig. 16). This could be however due to the level of degradation of the synthetic mouthpiece that broke during the testing of the C4 tone and resulted in air leakages that often result in a higher noise content (Damoradan, 2021, p. 5). A difference in partials produced between the 10mm cut in and the 15 mm cut in can also be seen (Fig. 15), where the 15mm cut in reed's spectrum shows a higher noise content, and less defined partial peaks, especially in the higher frequency domains. In the same figure, the relationship between the player's cane reed and the 10 mm "cut in" reed shows a consistently similar frequency difference (equal to one semitone) across all the compared partials. Figures comparing the player's cane reed to the 10 mm "cut in" in the tone C2, C3 and C5 show a similar frequency relationship (Figs. 14-17). Furthermore, the player noticed that he needed to apply more pressure to create a more stable sound, and the mouthpiece's higher resistance to the blowing pressure could have influenced the fundamental frequency of the sound as well.

4.4.2. Spectral analysis: sound color

The perceived sound color of wind instruments remains consistent across much of their playing range due to the pulse-forming sound production mechanism and the resonance and radiation characteristics of the resonator (Carral & Reuter, 2013). A formant is the relationship between frequency and the degree of amplification or resonance in any device, whether mechanical or electronic, that modifies, transmits, or radiates sound (Taylor, 2001). An investigation of the bassoon revealed that the consistent peak at around 500 Hz in the output spectrum originates from the source (the vibration of the reed), illustrating how any broad, fixed-frequency peak in a musical instrument's spectrum can function like a vowel formant, whether it results from resonances in the passive acoustic system or from source spectrum peaks (Fransson, 1966). All measured reeds (cane reed, 10 mm and 15 mm reeds) across all tones (C2, C3, C4, C5) show the same spectral peaks around 500 Hz (Figs 12-15). The presence of a prominent peak in the spectrum envelope is crucial to the perceived timbre of both the bassoon and oboe (Fransson, 1966), thereby the presence of the same spectral peaks in synthetic reeds confirm the evaluating player’s perceived similarity in sound when comparing his own cane reed to the synthetic reed.

Next to the presence of constant formant areas, the presence of constant spectral gaps in the spectra of wind instruments is also relevant for the sound color they produce (Voigt, 1975; Carral & Reuter, 2013). The presence of constant spectral gaps are visible well in the spectral analysis of all measured reeds (cane reed, 10 mm and 15 mm reeds) across all tones (C2, C3, C4, C5). Voigt (1975) found the gaps in the spectrum occur because the reed's closing time remains nearly constant, regardless of the playing frequency (p. 349). This view is regarded as the pulse forming theory, while the other major theory is called interference theory, claiming that the characteristic sound color of wind instruments arises from the resonances deviating from the harmonic structure of the reed or lip vibration, with the inharmonicity of the resonances caused by varying end corrections for each note, pointing again to the instrument's geometry (Carral and Reuter, 2013).

After the fifth partial tone, certain discrepancies between the cane reed and the synthetic reed are visible, with clearly defined overtones in the conventional reed that are less pronounced or missing entirely from the 3D printed reed. This could possibly be linked to the perceived higher noise content of the 3D printed reed, that could be explain by one of the common faults of additive manufacturing: sometimes cracks between layers are present that could result in air leakage which increases the noise content of the mouthpiece (Damoradan, 2021, p. 5).

There are differences in the frequency response between the 10mm “cut-in” and 15mm “cut-in” depth visible in the spectral analysis after the fifth partial as well (Figs. 15-16). The 15 mm “cut-in” reed’s fourth partial is more pronounced at the 500 Hz in case of the C3 tone (Fig. 15), however all other partials are less pronounced, especially the fifth and seventh being considerably weaker compared to the reed with 10mm “cut-in.” There isn’t enough data to make conclusions, however it might be possible that a higher “cut-in” results in the Bassoon’s known formant area of around 500 Hz to be more pronounced, while the higher partials are less pronounced resulting in a “duller” sound (Kopp, 2013).

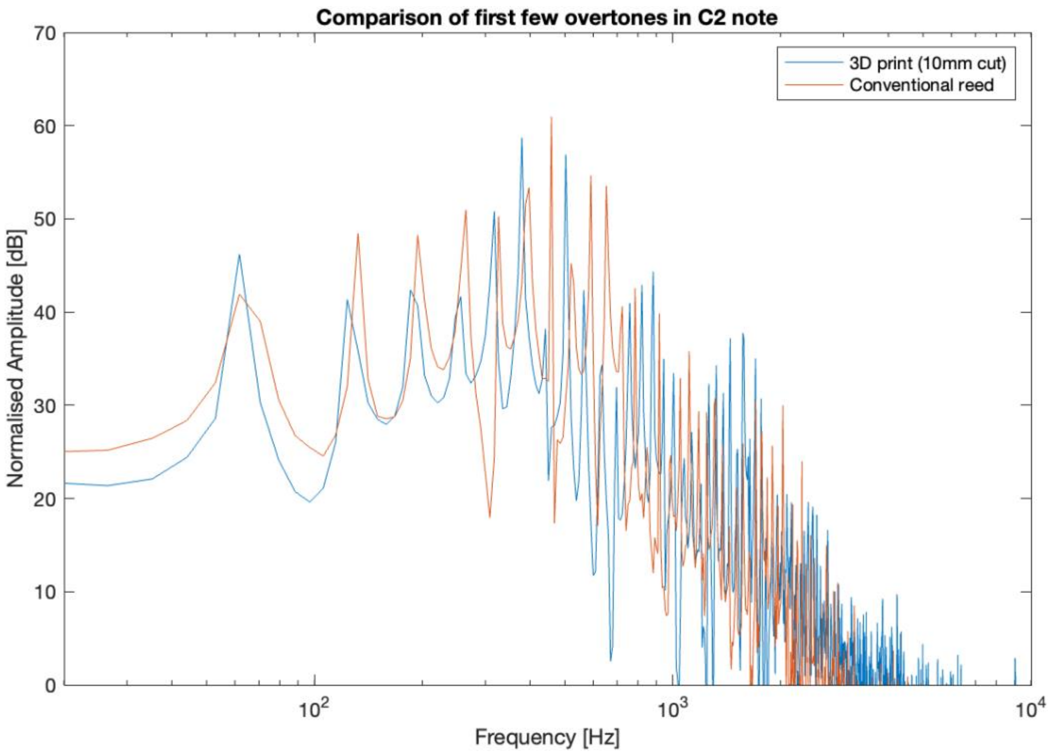

Figure 14. This figure is Showing the spektral analysis for the tone C2 recorded with a conventional reed, the 3D printed reed with 10mm “cut in” depth and the 3D printed reed with 15mm “cut in” depth.

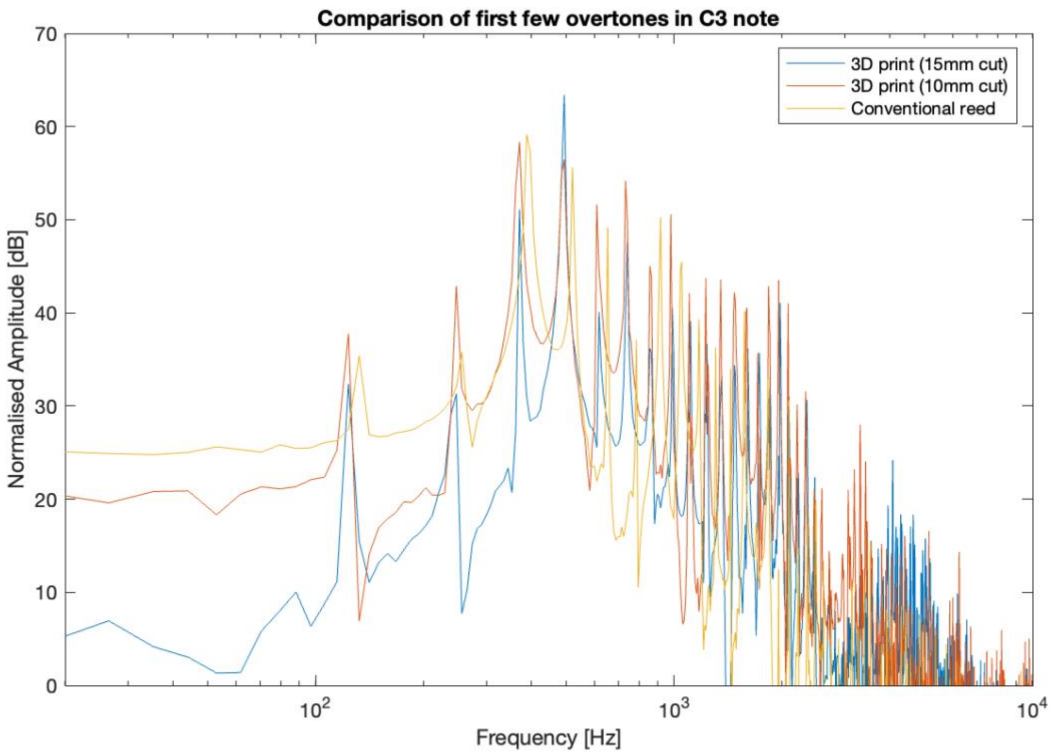

Figure 15. This figure is Showing the spectral analysis for the tone C3 recorded with a conventional reed, the 3D printed reed with 10mm "cut in" depth and the 3D printed reed with 15mm "cut in" depth.

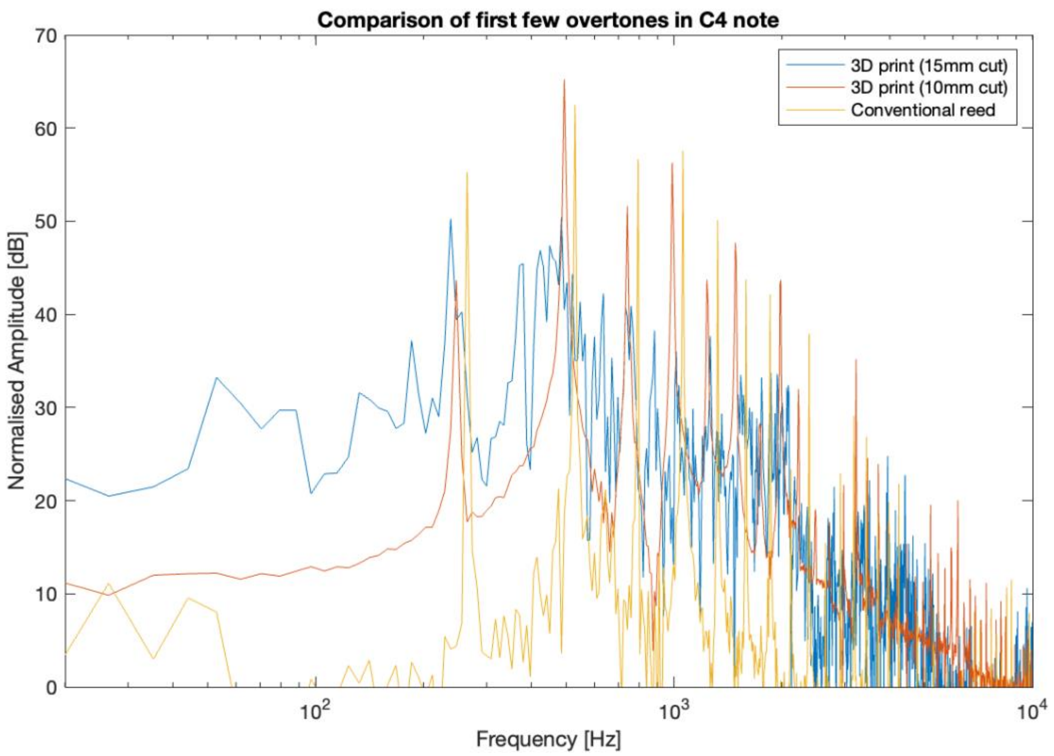

Figure 16. This figure is Showing the spectral analysis for the tone C4 recorded with a conventional reed, the 3D printed reed with 10mm "cut in" depth and the 3D printed reed with 15mm "cut in" depth.

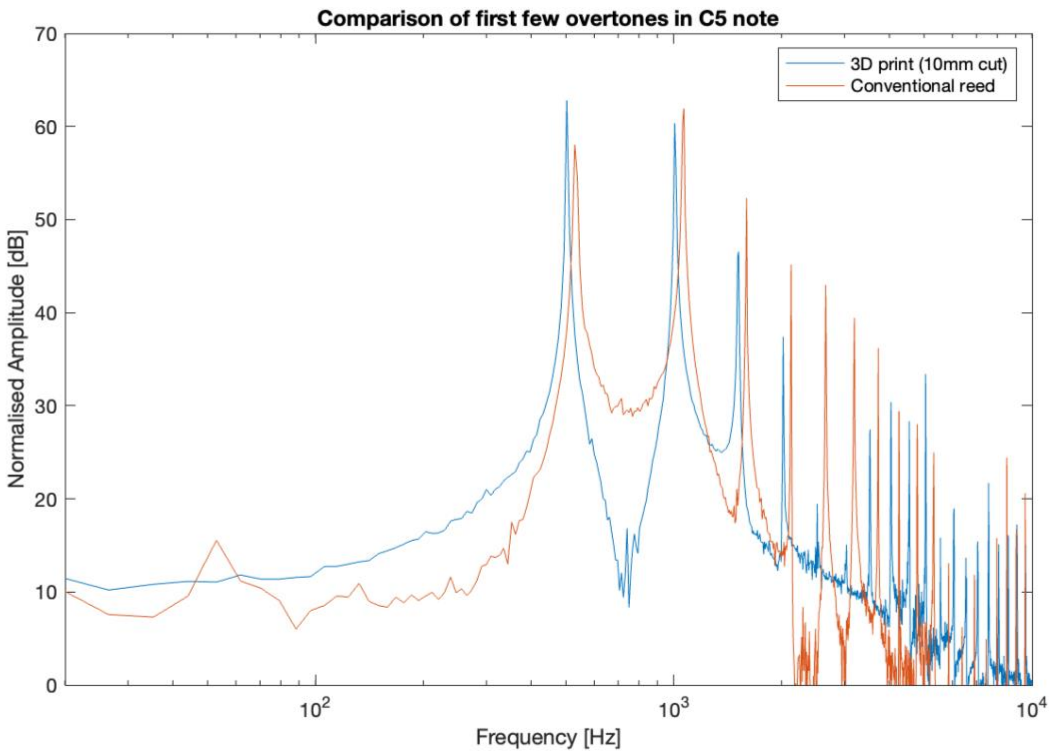

Figure 17. This figure is Showing the spectral analysis for the tone C5 recorded with a conventional reed, the 3D printed reed with 10mm "cut in" depth and the 3D printed reed with 15mm "cut in" depth.

4.4.3 Statistical analysis

The audio signal analysis was made with the tool PADMEA. (Czedik-Eysenberg, 2021, p. 59) The statistical analysis was made with jamovi (version 2.3) (2022), that found highly significant results in the aspects of Spectral flatness, spectral skewness and non-tempered energy ratio when comparing the cane reed, the 10mm cut-in depth synthetic reed and 15mm cut-in depth synthetic reed with each other. Spectral flatness measures the relative concentration or spread of energy distribution in a TFD, with high flatness indicating uniformly spread energy and low flatness indicating energy concentrated in specific regions (Boashash et al., 2015). Based on statistical analysis comparing the player's cane reed to the synthetic reed with both cut-in depths (10mm and 15 mm), the spectral flatness of the synthetics reed is significantly higher with both the 10mm cut-in depth $t\ (22)=5,431$; $p<0,001$ and also the 15 mm cut-in depth ($t=7,423$; $p < 0,001$) compared to the players cane reed. This mean that the noise content of the sound produced by the synthetic reed is significantly higher than of the player's cane reed.

Spectral skewness measures the asymmetry of energy distribution around the spectral centroid, with zero indicating symmetry, negative skewness reflecting more energy at lower frequencies, and positive skewness indicating more energy at higher frequencies, typical of harmonic-rich instrument sounds (Kazazis et al. 2022). Based on statistical analysis comparing the player's cane reed to the synthetic reed with both cut-in depths (10mm and 15 mm), the spectral skewness of the synthetics reed is significantly lower with both the 10mm cut-in depth $t\ (22)=-7,906$; $p<0,001$ and also the 15 mm cut-in depth ($t=-6,255$; $p < ,001$) compared to the players cane reed. In other words, the spectrum of the synthetic reed has a skew towards the low frequencies at both cut-in depths, which results in the synthetic reed to sound brighter.

The non-tempered energy ratio is a way of comparing how much energy is found in certain parts of an audio signal to the total energy in the sound. (Gómez & Herrera 2008) Based on statistical analysis comparing the player's cane reed to the synthetic reed with 15mm cut-in depth, the non-tempered energy ratio is significantly higher (4,566; $p<,001$), which indicates that the proportion of energy in the spectrum does not correspond to a tempered scale, which results in the sound of the synthetic reed with 15mm cut-in depth having a larger proportion of energy beyond the tempered scale resulting in a dirtier sound. On the other hand, comparing the synthetic reed at 10 mm cut-in depth to the same reed with 15mm cut-in depth reveals a significant difference in its non-tempered energy ratio ($t=-3,365$; $p<0,003$) indicating that the 15 mm reeds sound much more dirty (has a larger proportion of energy beyond the tempered scale) than the synthetic reed with 10mm cut-in depth.

10mm cut-in depth reed compared to cane reed	**15mm cut-in depth reed compared to cane reed**	**10mm cut-in depth reed compared to 15mm cut-in depth reed**
Spectral Flatness = Student's t (22)= 5,431; p<0,001 - Mean spectral flatness of 10mm cut-in depth group = 0,00963 - Mean spectral flattness of cane reed = 0,00613	**Spectral Flatness** = Student's t (19)= 7,42; p<0,001 - Mean spectral flatness of 15mm cut-in depth group = 0,0110 - Mean spectral flattness of cane reed = 0,00613	**Non-tempered Energy Ratio**= Student's t (19) = -3,37; p<0,003 - Mean Non-tempered Energy Ratio of 10 mm = 0,701 - Mean Non-tempered Energy Ratio of 15 mm = 0,864
Spectral Skewness= Student's t (22)= -7,906; p<0,001 - Mean Spectral Skewness of 10mm cut-in depth group = 4,453 - Mean Spectral Skewness of cane reed = 7,1108	**Spectral Skewness**= Student's t (19)= -6,255; p<0,001 - Mean Spectral Skewness of 15mm cut-in depth group = 4,5024 - Mean Spectral Skewness of cane reed = 7,11081	
	Non-tempered Energy Ratio= Student's t (19)= 4,57; p<0,001 - Mean Non-tempered Energy Ratio of 15mm cut-in depth group = 0,8641 - Mean Non-tempered Energy Ratio of cane reed group = 0,66883	

5. Evaluation

The evaluation of the synthetic reed created through additive manufacturing (AM) involves a detailed examination of its design, structural performance, and material characteristics. This chapter aims to systematically assess the reed's functionality, sound production capabilities, and overall viability as a substitute for traditional cane reeds. Drawing on insights from qualitative feedback from the player as well the spectrum analysis comparing the players cane reed with the synthetic reeds of 10 mm and 15 mm "cut in" respectively, this evaluation identifies key strengths and challenges while suggesting ways for future improvement.

5.1. Reed design and measurements

The reed created by additive manufacturing shows the importance of using the right proportions in the CAD design because they influence the frequency response of the mouthpiece. Firstly, the synthetic mouthpiece was too narrow at the end, so it couldn't be pushed onto the bocal for the desired length of 10-13mm without breaking, only to an extent of 3mm. The 10mm difference in length changed the desired length of the air column, that was probably the main reason for the change of pitch by a semi-tone in the instrument, also confirmed by the spectral analysis (Figs. 14-17). The synthetic reed manufacturer Légére solved this challenge by assembling their reed from two different materials. The thin front of the reed, responsible for vibrating properly, is from polypropylene and it is supported by a metal part that connects it to the bocal (Fig. 7) (Légére Reeds, n.d.). The metal tube ensures that the polypropylene part of their reed is never directly connected to the bocal and is therefore protected from rupture (Légère Reeds Ltd. n.d.). *Arundo donax* is one material, however its layers have very different properties (Kolesik et al., 1998). The two outer layers are hard enough to withstand force (Kopp 2003), in this case being placed on a bocal with a slightly narrower diameter then required for the perfect joining of the reed and the bocal. Consequently, the mouthpiece created with AM must have a more accurate design that a cane reed. Not every bassoon is of the same proportions, including the bocal, and the preferences of players isn't uniform either. Luckily, one of the main advantages of AM is the possibility to tailor custom designs for individual players (Negi, 2019, p. 13).

Looking at the exact measurements of the synthetic mouthpiece made with AM relevant for its sound and reproductivity, it has a total length of 53 mm and a tip aperture length of 12 mm. While the length of 53 mm isn't significantly deviating from the average length of 55-56 mm found the International Double Reed Society's webpage collecting high quality cane reed measurements, the tip aperture length is somewhat shorter that the shortest aperture length of 13.5mm, and significantly shorter than the average of 15 mm, out the 47 mouthpieces presented (International Double Reed Society & Scrapes journal, n.d.). As a result of these two main metrics, the AM mouthpiece is smaller than an average bassoon cane reed and will cause a shorter air column and the instrument will produce a higher frequency, if all other factors remain unchanged.

5.1.1 Aperture designs

The tube of the reed, encompassing the collar, throat, and butt, primarily serves to connect the blades to the crook or bocal (Kopp, 2013). The tube diameter of the synthetic reed is 6mm. The tip-to-tube ratio represents the width of the reed's tip divided by the tube's width (measured just above the collar or first wire), typically ranging from 1.5:1 to 2:1, such as a 15 mm tip width divided by an 8.5 mm tube width yielding a ratio of approximately 1.76 and will determine the aperture size (Kopp, 2013). In the case of the AM reed there is a tip-to-tube ration of 12mm to 6 mm, which corresponds to a ratio of 2:1. Apertures (Fig. 16), historically categorized as either wholly convex ("French") or with "collapsed corners" ("German"), though these terms are outdated, exhibit contrasting characteristics: convex shapes produce a lively sound with a sudden attack, while collapsed-corner shapes yield a more subdued sound with increased resistance and a more deliberate attack (Kopp, 2013). The tip-to-tube ratio of the synthetic reed is 2:1, and has therefore a wholly convex shape, clearly visible in figure 6. This tip-to-tube ratio also falls within the acceptable tip-to-tube range defined by Kopp (2013) and should therefore be able to produce a bassoon-like sound. The player said that the sound production of the reed was hard to control and it took him more physical effort to sustain the tones because the tip aperture was too wide with 2,5mm compared to his cane mouthpiece with 1,5mm. The tip-to-tube ratio is crucial in influencing the reed aperture (Kopp, 2013), and should therefore be used to make improvements in the CAD design to fit the preferences of individual players.

When Spanish cane is soaked it changes shape and expands in size (Bocur, 2019, p. 185). The most important obvious difference between soaked and not soaked canes is that only soaked canes are expected to produce sound (Ewell, 2017). Casadonte (1995) lists the expansion in volume occurring in clarinet reeds because of soaking, given in percentages: the greatest expansion occurs in its radial expansion (inside-to-outside) is 16.8%, tangential expansion (left-to-right) is 7.5%, and longitudinal expansion (tip-to-butt) is 4.5% (p. 244-246). Consequently, the swelling of cane should be taken into account when choosing designing measurements of the synthetic reed.

The fact that synthetic reeds don't have to be soaked to be used is one of their greatest advantages, however they also expand upon being moistened.

Kopp (2003) says soaking expands tip aperture which is a critical requirement for correct reed vibration, while letting the cane dry will result in the tip aperture being partially or fully closed. The importance of tip aperture was also explained by the expert player, who said a too wide tip aperture makes it hard to control and sustain played tones. He also said there is some variability in the preference among bassoonists, however the tip aperture of the synthetic reed would be labelled too wide by most of them (Fig. 8). It is clear, the design of the synthetic cane should resemble a soaked tip aperture if the AM material does not expand when coming in contact with water, however the synthetic reed's tip aperture in this study was too wide.

5.2 structural challenges and innovation

Mouthpieces made from Spanish cane are tied together from two reeds (Waterhouse, 2001). The same principle is applied by the company Légére by taking two synthetic reeds and gluing them together (Légère Reeds, n.d.). On the other hand, additive manufacturing allows for a unique innovation: printing the double-reed in one piece without assembling. During printing test runs it was attempted to print the two reeds separately, but these attempts failed because the FDM machine failed to print the complex geometries of the double reed with a satisfying accuracy. Creating the synthetic reeds as a unit on the other hand worked a lot better because this way the FDM machine didn't have to print fibers "in the air" – a result of printing a design with complex bending geometries (Gibson et al., 2015, p. 11-12).

Based on Campbell et al. (2003) describing reed vibration and the design of the "medium-hard Bassoon reed" made by the company le (Légère Reeds Ltd., n.d.) (Fig.

7), it was presumed that the synthetic double-reed created in this thesis won't produce any sound without separating the reeds starting from the tip aperture by cutting in. This presumption was tested and verified by the player, who couldn't produce sound when the reeds weren't separated yet. As a result, a new measuring metric was introduced by the name of "cut in depth" measuring the length (in mm) of the reed separation starting from the reed tip by cutting in with a bassoon knife tool, normally used by the player for the forming and making corrections to his cane reeds (Kopp, 2013). At 10mm and 15mm our player was able to produce sound, and differences in "cut in depth" had a significant impact on playability. The expert player, who has a lot of experience as a craftsman (Heinrich, 1991, p. 610), had difficulties controlling the "cut in depth." Even with the right tools, he didn't manage the material rapturing of the mouthpiece in the way he intended – highlighting a significant weakness of the mouthpiece created with AM. It is uncertain if this challenge can be solved by a different design, or rather by a different choice in material and AM manufacturing technology. Further research is needed to determine ideal "cut in depth," and if "cut in depth" can be controlled to the desired degree, or printing the mouthpiece as a whole instead of printing it in two separate parts will become an abandoned concept.

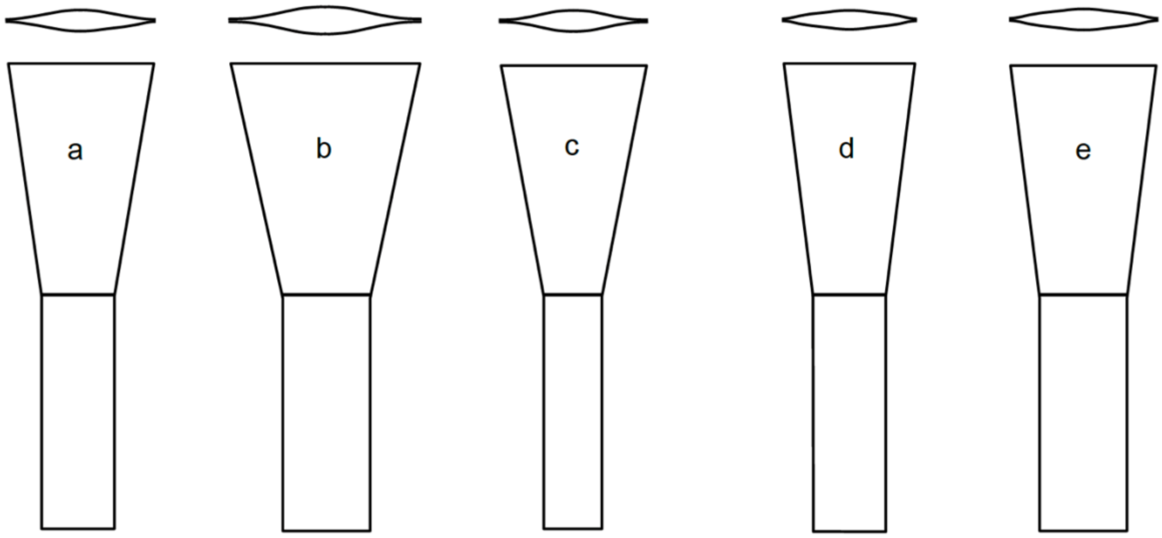

Figure 16. This figure is showing images of contrasting tip-to-tube ratios (below) and their corresponding apertures (above). Shape (a) represents an average ratio, while shapes (b) and (c) have larger ratios, and shapes (d) and (e) have smaller ones. The overarching principle holds more significance than the exact numerical ratios.

5.3. Structural reed changing techniques

The bassoonist's task to perfect his reed cane from the cane blanks is a laborious process which takes time and requires craftmanship (Heinrich, 1991, p. 610), however it also empowers him by having a wide variety of techniques to influence the geometry of a cane reed and thereby the sound of the instrument (Kopp, 2013). These techniques will be inspected from the perspective of usability in the case of the synthetic reed made by AM.

The expert player explained that bassoonists solve being too flat or too sharp by modifying their mouthpiece, concepts also presented by Kopp (2013). The player explained that If bassoonists are too flat, their first option is to cut off from the tip aperture horizontally, reducing mouthpiece length on both sides equally thereby reducing the length of the air column which should result in a higher pitch (Carse, 2002). Furthermore, the blade length influences the aperture size, therefore shortening the blades will result in a wider tip aperture because of a reduced tip-to-tube ratio, assuming all other factors remain constant (Kopp, 2013). Since the player was able to use his reed cutting knife to adjust the reed, it can be presumed that any experienced player should be able to cut off from the tip of a synthetic reed the same way they cut off from the tip of their cane reeds. However, this theory remains to be tested.

The player revealed the bassoonist’s second known technique, adjusting the reed wires. Wire adjustments are essentially manipulations of the three-dimensional reed tube’s form, with the wires serving as control mechanisms (Kopp, 2013). In the first type of wire adjustment, bassoonists soak the cane reed and increase the pressure between the canes by tying them closer with the upper wire (closest to the tip), resulting in pressure increase that produces a higher frequency (Gambill, 2024, p. 22-23). Flattening the first wire will tend to close the central section of the reed aperture, while opening the wire will usually result in opening the central section of the aperture (Kopp, 2013). Flattening or rounding the corners of the aperture can be influenced by adjusting the second wire. Wire manipulation can change the aperture form towards being wholly convex or having "collapsed corners," thereby influencing sound characteristics mentioned in the above section (Kopp, 2013). While it is obvious why these wire adjusting techniques cannot be used on a synthetic reed without wires, it is useful to understand the function of wire adjustment, so the implementation of mechanisms in synthetic reeds with similar effects can be considered.

According to the player, the third option is to pick a different cane design created by a reed maker, because if one chooses a narrower reed design, it will also produce higher frequencies. Reed makers rely on a combination of factors—including wire placement, trim or scrape, cane quality, and gouge thickness—which work alongside the chosen shaper to achieve the desired shape, forming an interconnected "recipe" (Kopp, 2013), usually a closely guarded secret critical to success (Campbell et al., 2004, p. 105).

The aperture corners of the synthetic reed were missing because the AM machine wasn't able to print them due to their thinness and complex geometry. The player noticed the mistake and added that players often cut these corners off to protect the cane reed from fracturing, since the corners are the most fragile parts of the mouthpiece and unwanted contact with them could break the reed in way that would make it unplayable. He also added that cutting of the edges does not influence the sound quality of the reed. Non the less, some bassoonists might be discouraged from using a synthetic reed without aperture edges. If using a higher quality FDM machine wouldn't solve the need for a high enough printing resolution to print the aperture corners, advancements in AM technologies improve printing accuracy rapidly (Gibson, 2015), so printing aperture edges with FDM technology should be possible in a couple of years. There are printing technologies that were used for additive manufacturing of wind instruments offering a significantly higher printing resolution like Electron beam melting (EBM), Stereolithography (SLA), Digital light processing (DLP) and Polyjet, with some being more than 1000 times more precise than FDM (Damoradan, 2021 p. 3-4). Since the player was able to make adjustments by cutting the synthetic reed, it can be presumed, that in the case of an accurately printed aperture edges, bassoonists would be able to use the technique of cutting of the edges on synthetic reeds if they wished.

The last technique for the adjustment of a reed depends on the material of the reed. Softer cane typically forms a smaller tube diameter, resulting in a higher tip-to-tube ratio, whereas harder cane forms a larger tube diameter, leading to a lower tip-to-tube ratio (Kopp, 2013). To manage softer cane, the player can: (a) narrow the tip after forming, (b) use no bevel or a smaller bevel on the tube, or (c) position the wires higher on the shape while shortening the profile. To increase the tip-to-tube ratio for harder cane, the player can: (d) use a larger bevel on the tube, (e) position the wires lower on the shape while lengthening the profile, or (f) carefully narrow the throat prior to forming using a file to maintain precise tolerances. Apparently, these techniques cannot be transferred onto the synthetic reed, so these measurements must be considered before manufacturing the reed, where the question of material selection will be of key importance.

5.4. Material and AM method choices

Arundo donax was composed of 3 separate layers from materials behaving differently (Kolesik et al., 1998). It is possible to replicate this structure by making a multi-material 3D print with a FDM printer (Kelly, 2022). For the created synthetic cane only one material was used, due to insufficient resources for a multi-material 3D print. As a result, the material for the synthetic reed needed to simultaneously replicate the hardness of two outside cane layers to be structurally stable (Kopp, 2003), and the flexibility (moderate stiffness) of the thick inner cortex to resonate easily. Consequently, the synthetic mouthpiece will be evaluated in the two separate categories of hardness and flexibility.

5.4.1. Material Hardness

The material hardness of the synthetic reed will be compared to cane reeds from the aspect of structural stability. The mouthpiece material was damaged from an attempt to insert it onto the bocal. One reason for the damage was that the diameter wasn’t wide enough. However, the mouthpiece didn’t resist low-level external impact – inserting the mouthpiece onto the bocal by minimal force. Possible explanations can be found in (a) either the design of how the two halves of the mouthpiece were molded wasn’t good enough, (b) the material used wasn’t hard enough (low resistance to abrasion) or both at the same time. Solutions may include a similar tying concept that is seen in cane reeds by using wiring (Waterhouse, 2001). In this case the cane’s inner cortex comes into direct contact with the bocal when the reed tube is inserted onto it. The second solution was presented by the synthetic cane reed manufacturing company Légére (Légére Reeds, n.d.), who used a metal part to reinforce the reed bottom (Fig. 7). From Légére’s solution it can be presumed that the company struggled to find a synthetic replacement matching cane’s all properties and probably settled on replicating only the thick inner cortex which serves as the vibrating element (Campbell et al., 2004). The hardness of the cane reed tube, where the outer two layers aren’t scraped away and serve for the structural stability of the reed (Kopp, 2003), was replicated by adding a metal part at the end of the synthetic reed tube (Légére Reeds, n.d.). Therefore, in replicating the cane reed with additive manufacturing it should also be considered to create the synthetic cane reed from two parts by printing a tube and blade separately from different materials and bound them together at a later stage, instead of printing the mouthpiece as a whole. A second solution could be to print the synthetic reed as a whole as it was done in this thesis and later add a similar wiring system like in the case of cane reeds with all its functions (Gambill, 2024, p. 22-24; Kopp, 2013). However, it is doubtful the wiring system will function the same way, since the blades are molded during AM and if the synthetic reed is hard enough to resist the pressure exerted by the wires. Alternatively, the two blades can be printed separately and combined with the wiring system resulting in a reed most similar to traditional methods, however the question of sufficient material hardness remains.

5.4.2. Material flexibility

The cane reed's two main parts are the tube and the blade (Gambill, 2024, p. 26). The hardness of the reed material is an important attribute for the tube, while its material flexibility is essential for the blades so they can resonate properly (Kopp, 2003). Since the first two layers are scraped away, the material stiffness of the cane reed's third layer (thick inner cortex) is compared to the 3D printed double reed from the viewpoint of how easily they resonate. The expert player said that the synthetic mouthpiece was too stiff and therefore could not produce a wide enough dynamic range. These findings correlate with Casadonte (1995), who found a decrease of stiffness when the cane reed is soaked that led to a better playability and resulted in lowering the frequency of the cane compared to unsoaked ones (p. 255). Still, the synthetic reed's stiffness was closer to the stiffness of a soaked Spanish cane than the unplayable unsoaked one. Stiffness can be changed by choosing a different material than PET-G (glycol-modified polyethylene terephthalate) or create a composite combining PET-G with other materials. The synthetic material polypropylene has properties that match the stiffness of *Arundo donax* to a high degree (Bucur, 2019, p. 574), however it can only be processed by powder bed fusion AM technology (Bourell et al., 2017, p. 660).

5.4.3. Material: density, stiffness and damping

Next, it will be evaluated how well the most important physical attributes of cane reeds for sound production were replicated: density, stiffness, and damping. The Spanish cane has moderate density, high stiffness, and quick damping (Kopp, 2003). The expert player reported higher stiffness and quicker damping than he’s used to in cane reeds. The player also found his cane reed to be lighter compared to the 3D printed reed indicating a higher density in the 3D mouthpiece, especially since the synthetic mouthpiece was smaller in size. An alternative to PET-G could be SLS nylon, a material with similar density to cane and good acoustical properties for building wind instruments, using Selective Laser Sintering (SLS) that has a significantly higher printing precision, however, has porous and rough surface that requires additional work in post-production and high manufacturing costs (Savan & Sivian, 2014, p. 542). The density of Spanish cane reed changes after it is thoroughly soaked, which can be seen from the weight or mass added by free water, that is 3.75 % (Casadonte, 1995, p. 256). The synthetic reed doesn’t have to be soaked, a fact confirmed during the testing phase as well. However, PETG also absorbs water with a rate of around 0.15%, and a weight variation around 0.3% (Moreno Nieto et al., 2021, p. 3). Comparatively, the often-used material for FDM additive manufacturing, also used to produce wind instruments (Damoradan, 2021, p. 3), PLA (polylactic acid) was reported to have a higher average weight increase of 2.5% when soaked according to Moreno Nieto et al. (2021). This shows that the water absorption properties of alternative materials for the production of synthetic reeds should be considered, because they can significantly affect density. As the synthetic reed gradually absorbed water during testing with the player, there was no visible change in its proportions, structure or the perceived sound. PET-G’s advantages are accessibility and cost effectiveness (Zvoníček et al., 2023, p. 13), non the less it has some setbacks when used to manufacture wind instruments. According to Spanou (2019), thermoplastics like PET-G change their stiffness with the change of temperature more than other materials and this can lead to inconsistencies in frequencies (p. 26). Measuring these inconsistencies was beyond the scope of this study, however the change in temperature between the players mouth (around 35 degree Celsius) and room temperature (around 20 degree Celsius) did not have significant enough effect to be noticed by the player, nor seen on the spectral analysis. PET-G has a higher density and produces vibrations in higher frequencies (Spanou, 2019, p. 26). This could explain why the spectral analysis and the statistical analysis comparing the synthetic reed with the players cane reed showed slightly higher peaks in higher frequency domains in favor of the synthetic reed made from PET-G.

Thermoplastics, including PET-G, have higher absorption properties, which was also reported by Martin et al. (2019) in a study to replace the horn of a 19th century phonograph (p. 5). When using a horn 3D printed (with FDM) out of PLA only, another thermoplastic, it absorbed a lot more high and low frequencies than when using a 3D printed horn composed of 80% PLA and 20% coper or 20% bronze respectively. The absorption properties of thermoplastics explain the quick damping of the 3D printed mouthpiece reported by the player.

A further aspect is that the Spanish cane’s fibers rotate in a specific way, that results in stability in all three plains and equal vibration in all directions (Kopp, 2003). The FDM additive manufacturing technology prints straight fibers, so in this sense it is more like true woods that have only one natural plane of strength (Kopp, 2003). True woods have their natural plane of strength along their longitudinal plane, the opposite to the synthetic reed whose layers are printed horizontally, so it makes sense that the synthetic reed broke horizontally during testing, along to the horizontally printed fibers where it is weak (Fig. 9). Interestingly, Kopp (2003) claims that because of its flexibility only being on one plane, wood would vibrate chaotically if at all. The player could produce stable sound. However, there were some rare instances where the played note suddenly jumped octaves – occurrences the player had no explanation for but were maybe the result of Kopp's theory.

6. Conclusion

There were attempts to use AM technology to produce mouthpieces for wind instruments. (Ozdemir et al., 2021; Rodríguez et al., 2023; Lorenzoni, 2013; Spanou, 2019) However, until the making of this experiment, there was no other academic research covering the 3D printing of bassoon mouthpieces or mouthpieces for other double reed instruments. Considering that this research field is mostly unexplored, the aim was to create a functioning mouthpiece with AM technology, whose overtone structure is more or less identical compared to conventional reeds. From this perspective, the envisioned task in this paper was successful. A perfect synthetic reed was never expected and during the manufacturing process several instructive mistakes were made that were systematically evaluated, while also listing possible solutions.

The significance of precise design parameters in the CAD model became evident during testing, as it is usually the case with wind instruments since the geometry of the instrument is crucial for its sound production (Damodaran, 2021). Measurements such as the reed's overall length, tip aperture dimensions, and tip-to-tube ratios emerged as critical factors influencing its performance. The inability to insert the tube of the synthetic reed onto the bocal in the desired length of 10-13mm, only in the length of 3mm, resulted in a lenghtened air column and a subsequently a pitch shift by a semitone downwards (Carse, 2002), also confirmed by the spectral analysis. Furthermore, the synthetic reed's dimensions, including its total length (53 mm) and tip aperture length (12 mm), deviate from standard cane reeds (International Double Reed Society & Scrapes journal, n.d.), contributing to altered acoustic properties, particularly a higher frequency output due to the shorter air column. The study identifies that the tip-to-tube ratio of the synthetic reed (2:1) aligns with acceptable ranges for bassoon sound production, usually between 5:1 and 2:1 (Kopp, 2013), yet the excessively wide tip aperture challenged playability, requiring greater physical effort from the player. While the convex aperture shape theoretically supports sound production, the wide aperture hindered tonal control, underscoring the need for tailored designs in future prototypes. Unlike cane reeds that expand when soaked, the synthetic reed's fixed dimensions eliminate this variability but necessitate precise pre-design measurements to emulate a soaked cane's properties (Casadonte, 1995; Bocur, 2019). The cane reed’s wire system enables significant alteration to its tip aperture shape and frequency response (Gambill, 2024), that are useful because of the high variability among cane blanks and bassoonist preferences (Kopp, 2013). A similar system is missing for the synthetic reed. However, AM technology is able to produce custom designs at low cost while consuming low amounts of time, therefore it seems a good fit for producing synthetic reeds for bassoonists (Negi et al., 2019).

Structurally, the synthetic reed demonstrated innovative potential through AM, particularly the ability to print the reed as a single unit, avoiding challenges in traditional multi-part assembly. However, difficulties in achieving precise geometries, especially aperture corners, highlight limitations in FDM technology's resolution, suggesting that advanced methods like SLA or PolyJet may be required for future prototypes (Gibson et al., 2015; Damoradan, 2021). Additionally, the study introduces the concept of “cut-in depth” as a critical metric for functional reed separation, though challenges in controlling this parameter revealed material and design weaknesses, revealing the need for further refinement.

The material analysis revealed that the PET-G synthetic reed exhibited higher density and stiffness compared to Spanish cane (Kopp, 2003; Spanou, 2019), resulting in limited dynamic range and quicker damping, both crucial for sound quality. While the reed's stiffness approximated that of a soaked cane, its increased density suggests a need to explore alternative materials, such as polypropylene or SLS nylon, to better replicate the acoustical properties of cane reeds (Bourell et al., 2017; Savan & Sivian, 2014). There were no changes observed to refute that PET-G's low water absorption rate minimized dimensional changes during testing (Moreno Nieto et al., 2021). Furthermore, there were also no apparent changes to confirm an altered frequency response by temperature fluctuation because of PET-G's sensitivity to temperature change (Spanou, 2019). However, these parameters weren't the focal points in thesis, so smaller changes could have been overlooked.

Collectively, these findings affirm the viability of AM synthetic reeds as a substitute for cane reeds, contingent on enhanced design precision, material selection, and technological advancements in manufacturing methods. At the same time, the findings seem to confirm general theories on the functioning of bassoon reeds. The interest in using alternative materials to produce wind instruments is relatively recent and the usage of AM in the field of wind instrument making is mostly unexplored (Bucur, 2019). Especially since AM machines were first made commercially available in 1986 (Schmidleithner & Kalaskar, 2018).

Unfortunately, it is therefore hard to compare findings in this thesis to other findings in the field. The optimistic outlook for this thesis is only to give researchers and reed manufacturers a point of departure for future studies. Firstly, what measurements to use and what factors should be counted in the CAD design. Secondly, it suggests AM methods and their combination with materials most suitable for synthetic reeds as per current stand of research. And lastly, methods to test and evaluate the synthetic reed. The study shows that the main practical advantage of using AM for double-reed mouthpieces is the possibility of customization to satisfy the individual needs of players. Furthermore, it can replace the players highly time-consuming labor to manufacture each read by himself and eliminate the time required to properly soak the cane reed, since synthetic materials are playable without soaking.

The limitations of this study are great, which in a way was also required because of the large number of possibilities in additive manufacturing. First, the only used AM technology in this study is FDM because of budget and time constrains. There are 6 other used AM technologies for the manufacturing of wind that are known (Damoradan, 2021), while there being other AM technologies that maybe haven't been tried in this field (Gibson, 2015). While each AM technology limits the materials that can be combined with it, there are 30 listed material categories by Bourell et al. (2017), with the possibility to combine them in form of blends or composites (Picard et al., 2020), like in the case of FDM powders that allow mixing, which allows a high number of possibilities to be tried in finding the right material. It is possible to narrow down the search to the required acoustical and material properties like elasticity and hardness to replicate cane reeds (Bocur, 2019), however materials that seemed like a good match to replicate the properties of cane based on literature like polypropylene and SLS nylon could not be tried because of the unavailability of AM machines they require. Based on literature PET-G was selected (Zvoníček et al., 2023), however other materials usable by the available FDM machine weren't tested. In the testing phase only one expert player was used, and increasing the number of expert opinions would improve the sample size. Manufacturing more prototypes should also be advised to have backups if the synthetic reed breaks, as it did during testing. This should also be done because faults like cracks in the microstructure of the mouthpiece can arise during layer binding that aren't always noticeable at first (Bourell et al., 2017). Cracks can significantly compromise the sound production of the mouthpiece, lead to a higher noise content and inconsistencies in the mouthpiece's frequency response (Damoradan, 2021).

A future research direction would be to try all AM methods, especially those with a better printing resolution than FDM for a higher design precision, which is essential, while using materials with most fitting acoustical and material properties.

The overall research process was an effective way to understand the preferences of a bassoonists, because when they are using synthetic reeds, the playability of mouthpiece changes in an unusual way for the player and can learn about some of his preferences he might not even know about. This knowledge in turn can lead to creating a better mouthpiece. It is obvious, that If bassoonists can design and print their own synthetic reed, the testing and evaluating phases of perfecting a synthetic reed would shorten significantly. Therefore, it might seem to require significant effort, but those who want to create a synthetic reed should learn to play the bassoon first, if they want to design and create reeds with AM in the long run.

In conclusion, this study represents a pioneering step in the exploration of additive manufacturing (AM) for producing synthetic reeds for double reed instruments, while specifically focusing on the bassoon. By demonstrating the applicability of AM in this context, this thesis intends to open a pathway for future advancements in reed design and manufacturing. The findings underline the importance of precise design parameters, material selection, and advanced AM technologies, while acknowledging the challenges posed by current limitations in resolution and material compatibility (Damoradan, 2021).

This work not only provides a foundational understanding but also encourages further investigation into the interplay between material properties, design, and acoustics in reed manufacturing. As AM continues to rapidly evolve, it offers exciting possibilities for customization, efficiency, and accessibility for musicians and manufacturers alike (Dixit, 2022). Moving forward, embracing a systematic, iterative approach will be crucial in addressing these challenges and fully harnessing the potential of AM in transforming the field of wind instrument production.

The broader implication is clear: by combining technological innovation with musical artistry, researchers and musicians alike can redefine traditional boundaries, enhancing both the creative and practical aspects of instrument design. The future of synthetic reed manufacturing lies in collaboration, experimentation, and pushing the boundaries of what is possible.

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