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CNC technology in production of musical instruments

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Abstract: This study explores the integration of CNC (Computer Numerical Control) technology in the production of musical instruments, focusing on its benefits in precision, efficiency, and customization. While CNC technology offers significant advancements, it poses challenges to traditional craftsmanship, including the potential loss of uniqueness and artisanal skills. The study recommends a balanced approach, combining CNC with traditional techniques, to enhance production while preserving cultural heritage. Emphasizing education, research, and transparent communication, this work advocates for the thoughtful adoption of CNC technology to innovate within the musical instrument industry while maintaining its artisanal roots.

Keywords: CNC Technology, Musical Instrument Production, Precision Manufacturing, Hybrid Production Methods

INTRODUCTION

CNC (Computer Numerical Control) is an advanced technology that plays a key role in modern manufacturing, enabling the automation and precise control of various industrial machines through computers. CNC technology integrates computer software with production machines, allowing the automation of machining processes such as milling, turning, drilling, laser cutting, and many others. CNC machines can operate on a wide range of materials, including metals, wood, plastics, and even glass (Xiao et al. 2021; Lan et al. 2024).

The central element of a CNC system is the computer, which converts a digital design, usually created using CAD (Computer-Aided Design) software, into detailed machine code instructions (most commonly in G-code format). This code describes every movement of the working tools, such as milling cutters or drills, along with parameters like rotational speed, cutting depth, and angles of inclination. The CNC machine reads these instructions and performs precise operations, minimising the possibility of errors that may occur with manual control.

CNC technology has revolutionised the industry by introducing capabilities that were previously difficult to achieve. With its high precision and repeatability, CNC machines are ideal for both mass production and the creation of complex, custom designs. The automation provided by CNC significantly reduces production time, lowers costs, and enables the production of intricate shapes that would be difficult or impossible to create by hand (Lan et al. 2024).

In addition to precision and automation, CNC also allows for integration with other technologies, such as CAM (Computer-Aided Manufacturing) systems, which further optimise production processes. CNC makes it possible to monitor and control production quality in real-time, which is crucial in industries where even the smallest deviations can impact the final product's quality (Groover 2013)

HISTORY AND DEVELOPMENT OF CNC TECHNOLOGY

CNC technology has its roots in earlier methods of machine control, such as NC (Numerical Control). Numerical control (NC) emerged in the 1940s and 1950s as a result of research on production automation conducted in the United States. One of the pioneers in this field was John T. Parsons, who, together with engineers from MIT (Massachusetts Institute of Technology), worked on automating the production of aircraft turbine blades. Their efforts led to the creation of the first NC system, which used punched tapes to control machine movements.

The first NC machines were analog-controlled and had limited functionality due to the technology available at the time. However, the groundwork was already being laid for the development of more advanced systems that would lead to CNC.

The true revolution occurred in the 1960s when computers were introduced into NC systems, leading to the development of CNC. The introduction of digital computers significantly increased precision, flexibility, and control over the production process. CNC machines could now interpret more complex instructions, allowing for the production of more intricate parts with greater accuracy.

In the 1970s and 1980s, CNC technology became increasingly common in industry, particularly in the production of machines and tools, as well as in the automotive and aerospace industries. The introduction of microprocessors into CNC systems further enhanced their capabilities, enabling more complex operations and better integration with other production systems, such as CAD (Computer-Aided Design) and CAM (Computer-Aided Manufacturing).

From the 1990s to the present, CNC technology has continued to evolve, gaining precision, speed, and integration capabilities. Modern CNC systems are capable of processing vast amounts of data in real time, allowing for even more precise operations. The application of CNC has also expanded into new areas, such as electronics manufacturing, biotechnology, and even the art industry.

Contemporary CNC machines can be programmed in a fully integrated environment where design, simulation, and then production occur in a single cycle. These machines can also communicate with other machines and systems within the framework of Industry 4.0, enabling the automation of entire production lines and factories.

CNC technology has also become more accessible due to the development of open-source software and the availability of cheaper, smaller CNC machines, allowing its use not only in industry but also in small workshops and by hobbyists.

Objective of the Study

The objective of this study is to investigate the impact of CNC technology on the production of musical instruments, considering its advantages, disadvantages, and effects on traditional craftsmanship methods. The study aims to analyse contemporary applications of CNC, identify the main concerns of manufacturers, and recognise development trends in the context of integration with other technologies and innovations.

MATERIALS AND METHODS

A critical analysis of available literature was conducted as part of the review, focusing on the application of CNC technology in the production of musical instruments. Existing research, scientific articles, books, and online sources discussing the impact of CNC on the instrument production process were identified. Both the advantages and disadvantages of using CNC technology in this field were analysed. A series of interviews were conducted to gain insights from experts in musical instrument manufacturing. The Delphi method was employed to explore expert opinions on the impact of CNC technology. The data collected from experts allowed for the identification of key issues related to the use of CNC in instrument production.

Expert interviews were conducted with craftsmen, musical instrument manufacturers, and engineers specialising in CNC technology. Experts were asked about their experiences, concerns, benefits, and challenges associated with using CNC technology in instrument production. The results of these studies provided valuable insights into the practical aspects of CNC application.

The findings from the literature review, the Delphi method, and expert studies were compared. Conclusions regarding the impact of CNC technology on musical instrument production were based on the analysis of the collected data. Development trends and opportunities for integrating CNC technology with other innovations in this field were also identified.

UTILISATION OF CNC TECHNOLOGY IN MUSICAL INSTRUMENT PRODUCTION

CNC technology has found widespread application in the production of musical instruments, contributing to increased precision, repeatability, and efficiency in manufacturing processes. Thanks to CNC, musical instrument manufacturers can create components with highly intricate shapes that were previously difficult or even impossible to produce by hand (Wu and Li 2016). Here's how CNC is utilised at various stages of musical instrument production:

CNC machines are used to cut and shape the bodies of guitars, violins, and other string instruments from blocks of wood. With CNC, it is possible to achieve identical body shapes with precisely defined dimensions, which impacts both the sound quality and the aesthetics of the instrument. CNC machining allows for precise milling of fingerboards and necks, including cutting fret slots and shaping the neck profile. This ensures that all instruments have identical characteristics, which is crucial for playability and intonation. CNC machines are also employed to create intricate inlays and decorations on bodies and fingerboards, significantly enhancing the aesthetic value of the instruments (Xiao et al. 2021).

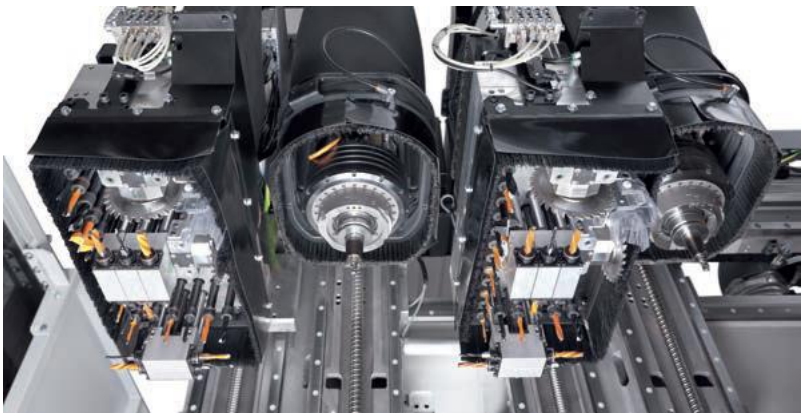

Fig 1. Milling tools and aggregates used in a Biesse CNC nesting machine. [Biesse Rover B FT catalogue]

In the production of wind instruments such as saxophones, trumpets, and flutes, CNC enables precise turning and milling of bodies and mouthpieces from metals like brass or silver. The precision of CNC is crucial for ensuring proper airflow and sound quality. In wind instruments, where complex key mechanisms are essential for playing, CNC is used to precisely cut and assemble these components. This ensures that the mechanisms operate smoothly, which is vital for performers.

CNC is used in the production of keys and hammer mechanisms in pianos and grand pianos. Precise cutting and machining ensure that each key has the ideal dimensions and weight, which is necessary for a consistent feel during play. CNC enables the production of intricate

piano and grand piano cases, which are not only aesthetically pleasing but also impact the instrument's acoustics. Precise milling allows for the creation of perfect joints between structural elements, ensuring the stability and durability of the instrument (Xiao et al. 2021).

The technology is used to shape drum shells, whether wooden or metal. The precise machining of the shell affects resonance and sound quality. CNC allows for the production of precise tuning components, such as screws and hoops, which are crucial for tuning the drums (Wu and Li 2016).

CNC technology allows for easy customisation of instruments, such as cutting unique patterns and shapes or adding special inlays tailored to the client's specifications. CNC is also used in the prototyping process of new instrument models, enabling quick testing of different shapes and designs before beginning mass production.

Fig. 2. Production phase of Fender guitar bodies. [https://www.haas.co.uk/resources/our-customers/industry/the-fender-custom-shop/]

ADVANTAGES OF CNC TECHNOLOGY

One of the most significant advantages of CNC technology is its ability to deliver exceptional precision and repeatability in production. CNC machines are computer-programmed, allowing for precise control over every stage of material processing. This enables achieving tolerances on the order of micrometres, which is crucial in the manufacturing of components requiring high accuracy, such as parts for musical instruments (Lan et al. 2024).

CNC precision eliminates many issues that can arise in manual processes, such as inconsistent quality, human error, or dimensional deviations. For example, in the production of string instruments like guitars, CNC technology allows for cutting bodies and necks with sub-millimetre accuracy, ensuring that each instrument meets specified quality standards. Such a high level of precision is essential for ensuring excellent intonation and playing comfort, which is particularly important for professional musicians (Xiao et al. 2021).

The repeatability offered by CNC means that every subsequent unit of the produced item is identical to the previous one. This is especially important in mass production, where consistent product quality is expected. Thanks to repeatability, manufacturers can maintain a high standard of quality while simultaneously increasing production efficiency, leading to greater customer satisfaction and the establishment of a strong brand presence in the market.

Fig. 3. A CNC machine used to make sure all the frets of the guitar are at their optimal place on a guitar neck. [https://facfox.com/docs/kb/cnc-machining-for-musical-instruments-how-technology-enhances-artistry]

Another key advantage of CNC technology is the savings in both materials and time. Machining processes carried out using CNC are planned and optimised by computer, which minimises the amount of production waste. With precise control, CNC machines can maximise the use of available material, cutting only what is necessary without excessive waste of resources.

DISADVANTAGES OF CNC TECHNOLOGY IN MUSICAL INSTRUMENT PRODUCTION

Although CNC technology offers many benefits in the production of musical instruments, it also has certain drawbacks that can affect the final quality and uniqueness of the instruments.

One of the main criticisms of CNC technology in the production of musical instruments is the lack of uniqueness and individuality. In traditional craftsmanship, each instrument is made by hand, which gives it unique features and character. Every craftsman has their own style and techniques, which can lead to subtle differences in the sound and appearance of the instrument (Vogel 2006).

With CNC, instruments are produced based on a digital model, leading to the creation of identical copies. While this ensures high repeatability and quality, it removes the unique character from the instruments. For many musicians, especially those who value tradition, handcrafted instruments hold greater value because they are perceived as more authentic and full of personality (Jacoby 2018).

This is most evident in the creation of violins and other string instruments. A key requirement for a professional instrument to be considered "master-level" is that it must be

entirely crafted by a single luthier. If an instrument is made by several people or by a machine, it automatically loses the "master-level" title. The world's top musicians choose only master-level instruments—those of the highest quality, crafted with meticulous attention to detail and created using the luthier's years of experience and knowledge. Such an instrument cannot be made by any machine, regardless of the technology or the operator's expertise (Dahlig-Turek and Pomianowska 2014).

Investing in CNC technology involves high initial costs. Purchasing CNC machines and CAD/CAM software and training employees to operate them is a significant expense, which can be a barrier for small artisan workshops and manufacturers.

Although the long-term benefits of automation can lead to savings, the initial costs may be too high for some businesses. As a result, these companies may be forced to seek alternative production methods or limit their offerings, which could affect their competitiveness in the market.

CNC technology is transforming the way musical instruments are made, leading to the gradual decline of traditional craftsmanship skills. Handcrafting instruments is a process that requires years of learning and practice. These skills, passed down through generations, are part of the cultural heritage that could be lost if CNC technology becomes the dominant standard in production (Sołtan 1978).

While CNC provides precision and efficiency, it cannot replace the intuition, experience, and finesse of a craftsman who can adjust production techniques to the specific characteristics of the material or the individual requirements of a client. The loss of these skills could impact the quality and diversity of instruments available in the market.

Despite its advanced technological capabilities, CNC machines can encounter certain limitations in material processing. Some unique or difficult-to-machine materials, such as exceptionally hard or unusual types of wood, may pose challenges during CNC processing. In such cases, manual techniques may be more effective and precise.

Additionally, certain operations, such as delicate carving or inlay work, may require exceptional finesse and sensitivity, which are difficult to achieve with CNC machines. While CNC is extremely precise, it may not fully meet the demands of the more artistic aspects of instrument production that require a personalised approach and creativity.

Production based on CNC technology requires constant access to advanced software and hardware. Technical issues, such as machine malfunctions, can lead to production downtime, negatively impacting schedules and increasing production costs. The need for regular maintenance and software updates also generates additional expenses and requires adequate technical support.

Dependence on technology also means that any changes or errors in programming can affect the entire production run. Without proper control protocols, there is a risk of producing a large number of defective products, which can lead to financial losses and damage to the company’s reputation.

THE PROCESS OF MUSICAL INSTRUMENT PRODUCTION USING CNC TECHNOLOGY

The production of musical instruments using CNC technology is an advanced process that combines traditional craftsmanship with modern technology. CNC machines enable precise material processing, which is crucial for achieving excellent sound quality and instrument aesthetics. The production process consists of several key stages, including design, material selection, component machining, assembly, and finishing (Krzysik 1984; Corradi et al. 2017; Xiao et al. 2021).

The production of a musical instrument using CNC technology begins with the creation of a digital model of the instrument in CAD (Computer-Aided Design) software. The designer

creates a detailed plan for each component of the instrument, considering all requirements related to shape, dimensions, and materials. The CAD model serves as the basis for generating the machine code (G-code) that will control the CNC machine during machining.

Digital models can be created from scratch, which is typical when designing new instruments, or they can be based on existing designs that are digitally scanned and converted into a digital format. For instruments such as guitars or violins, CAD models include detailed data on the body, neck, fingerboard, and any inlays or decorations.

The next stage involves selecting the appropriate materials for the instrument's production. Materials are crucial for the sound and durability of the instrument. For wooden instruments like guitars, violins, or pianos, carefully selected types of wood such as maple, mahogany, spruce, or ebony are used. Metals such as brass, stainless steel, or aluminium are also utilised in the production of wind and percussion instruments.

The material is prepared for machining through proper cutting and drying, ensuring its stability and durability. For wood, the drying process is particularly important to prevent warping and cracking during further processing (Kamiński and Świrek 1972).

The main production phase involves machining the selected materials using CNC machines. CNC machining consists of several steps, depending on the type of instrument being produced (Xiao et al. 2021).

String Instruments (Guitars, Violins): CNC machines are used to cut the bodies and necks from blocks of wood. The milling process also shapes the interior of the body, where electronic components or other elements are housed. CNC technology allows for the precise cutting of fret slots, which is crucial for achieving proper intonation (Góralski 1996; Vogel 2006).

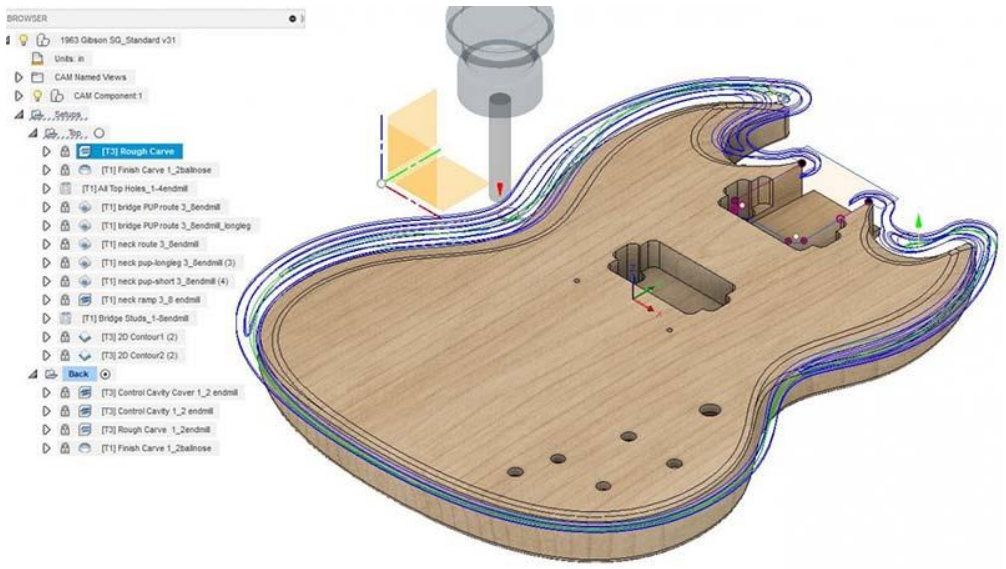

Fig 4. A visualization of the guitar body making process on a CNC machine. [https://www.eagletec-cnc.com/news/best-3-cnc-routers-for-guitar-making.html]

Wind Instruments (Saxophones, Flutes): CNC is employed to shape the bodies and mouthpieces from metal. Processes such as turning and milling enable the precise creation of components that affect airflow and sound quality. CNC machines are used to turn and mill drum shells, ensuring a perfectly round shape and appropriate wall thickness, which are vital for resonance. During CNC processing, all stages are computer-monitored, allowing for immediate adjustments and ensuring consistent production quality.

After all components have been machined, the instrument is assembled. For string instruments, assembly involves joining the body and neck, installing the bridge and saddle, and fitting the strings. In wind instruments, assembly includes putting together the body, fitting the key mechanisms, and attaching the mouthpieces.

The precisely crafted parts allow for the exact fitting of components, which is crucial for the acoustic properties of the instrument. Assembly is carried out using both machines and manual methods, enabling quality control at every stage.

The final stage of production is the finishing of the instrument. For wooden instruments, such as guitars, this involves sanding, varnishing, polishing, and applying decorative elements. The finishing process is not only important for the instrument's aesthetics but also affects its sound—proper surface finishing can enhance resonance and tone quality.

After the finishing process is complete, the instrument undergoes testing for sound quality, intonation, and the functioning of mechanisms. These tests are conducted both by machines, which measure acoustic parameters, and by musicians, who evaluate the instrument for playability (Konecki 2000).

EXAMPLES OF MODERN APPLICATIONS OF CNC TECHNOLOGY IN MUSICAL INSTRUMENT PRODUCTION

Contemporary companies in the musical instrument manufacturing industry are increasingly using CNC technology to streamline production processes and improve the quality of their products (Kneule 1976). Below are specific examples of how CNC is being applied in well-known musical instrument manufacturing companies.

Fender Musical Instruments Corporation

Fender is one of the largest guitar manufacturers in the world, and CNC technology is crucial in their production process. In Fender's production facilities, CNC machines precisely cut and mill the bodies of electric guitars, such as the Stratocaster and Telecaster, with high accuracy, ensuring consistent quality and perfect component fit. CNC is used to shape the neck profile, cut fret slots, and install components like the truss rod (neck reinforcement rod). This ensures that each guitar has a perfectly fitted neck, which enhances playing comfort and intonation. CNC technology also enables the precise cutting and installation of inlays on guitar fingerboards, allowing for the creation of both standard and custom designs.

Gibson Guitar Corporation

Gibson, known for producing luxury guitars, also utilises CNC technology to ensure the high quality of their instruments. At Gibson, CNC is used for the precise turning and milling of guitar bodies, such as those of the Les Paul and SG models, to achieve perfect shapes and dimensions. CNC technology allows for the exact preparation of wood blocks used in production, which is crucial for maintaining the high sound quality of the instruments. CNC facilitates the drilling of holes for bridges, pickups, and other mounting elements, speeding up the production process and ensuring precise component alignment (Gibson 2024).

Yamaha Corporation

Yamaha is a global leader in musical instrument production, with CNC technology playing a key role, particularly in the precise shaping of keyboards, ensuring the perfect fit for keys and hammer mechanisms. CNC is also applied in the production of precise metal components, such as the bodies of trumpets and saxophones, achieving excellent sound quality and reliable mechanisms. Moreover, CNC enables the creation of components with complex shapes and high precision, which is essential for maintaining the high quality of Yamaha instruments (Yamaha 2024).

Fig. 5. Photo of Gibson factory, [https://www.tennessean.com/gcdn/-mm-/274b047445dc14efd272722bf398aec40f00b496/c=0-160-3072-1888/local/-/media/Nashville/2014/04/15/-nasbrd05-03-2012tennessean1s00120120502img-gibson004.jpg20102.jpg?width=3072&height=1728&fit=crop&format=pjpg&auto=webp]

DW Drums (Drum Workshop Inc.)

DW Drums, a manufacturer of high-quality drums, utilises CNC technology in production to turn and mill drum shells made of wood and metal, allowing for precise fitting and achieving optimal sound quality. CNC machines are also employed in the production of precise mounts, hoops, and other drumming accessories, enhancing the durability and functionality of the instruments. CNC enables the creation of unique designs on drum shells, allowing for the customisation of instruments according to customer requirements (DW Drums 2024).

Pearl Drums

Pearl Drums, a renowned drum manufacturer, employs CNC technology to produce the precise turning of drum shells, ensuring perfect shape and wall thickness, which is crucial for achieving the desired resonance. CNC technology is also used in the production of percussion mechanisms, such as pedals and mounts, ensuring their high precision and reliability. CNC allows for the testing and optimisation of components, enabling products to be tailored to the specific requirements and expectations of customers.

THE FUTURE OF CNC TECHNOLOGY IN MUSICAL INSTRUMENT PRODUCTION

CNC technology plays a key role in modern musical instrument production, but its development does not occur in isolation. The integration of CNC with other technologies and emerging innovations opens new possibilities that could revolutionise the way musical instruments are designed and manufactured. In particular, current trends include the integration of CNC with 3D printing, robotics, and other technologies, which allow for greater precision, flexibility, and efficiency in production (Forum Akademickie 2002**)**.

Integration of CNC with 3D Printing: 3D printing, also known as additive manufacturing, is a technology that enables the creation of objects by layering material based on a digital model. The integration of CNC with 3D printing opens new possibilities in musical instrument production, offering a range of benefits. 3D printing allows for rapid prototyping and the introduction of individual modifications to instrument designs. Combined with CNC, it becomes possible to create complex components, such as guitar bodies or acoustic elements,

that can be customised to meet specific client needs. An example is the use of 3D printers to produce unique decorative parts, which are then precisely machined using CNC equipment.

Complex Geometries and Composite Materials: 3D printing enables the creation of components with complex geometries that are difficult to achieve using traditional machining methods. After printing, these parts can undergo further processing on CNC machines, allowing for optimal acoustic and aesthetic properties. This technology also allows for the use of composite materials, which can enhance the durability and sound qualities of instruments.

Repair and Restoration: In cases where rare or unique instruments are damaged, 3D printing can be used to produce missing or broken parts, which are then precisely fitted and assembled using CNC technology. This process can aid in the preservation and restoration of historical instruments.

Integration of CNC with Robotics: Robotics, when combined with CNC technology, can significantly enhance the efficiency and precision of musical instrument production. Here are a few areas where this integration offers benefits:

Automation of the Production Process: Robots can work in tandem with CNC machines to automate processes such as material loading and unloading, precise positioning of elements for machining, and transferring finished components to the next stages of production. An example of this is the use of robots to load wooden blocks onto CNC machines in guitar factories, which increases efficiency and reduces production cycle time.

Precision Finishing: Robots can be used for precision finishing tasks such as sanding, polishing, and applying protective coatings. Combined with CNC technology, robots can perform repetitive tasks with accuracy that are difficult to achieve manually, ensuring a high-quality finish (Calvano et al., 2023).

Complex Assembly Operations: Robots can also support complex assembly operations, such as assembling and adjusting instrument mechanisms. Robotics enables precise fitting of components and their assembly with minimal risk of errors, which is especially important in the production of instruments that meet high-quality standards (Blümich et al. 2020).

Potential Innovations and New Opportunities: CNC technology, when combined with other modern solutions, has the potential to introduce many innovations in the production of musical instruments. Here are a few areas where further development is expected:

Smart Manufacturing Systems: The use of artificial intelligence (AI) to analyse data from production processes can improve efficiency and quality. AI can monitor machining parameters in real time, identify potential issues, and optimise CNC machine settings, leading to increased precision and reduced waste.

Advanced Material Technologies: The development of new materials, such as nanomaterials or phase-change materials, could impact the way musical instruments are made. CNC technology will be able to process these innovative materials, potentially resulting in instruments with unique acoustic properties and enhanced durability.

Real-Time Customization: Integrating CNC with technologies like augmented reality (AR) or virtual reality (VR) could enable customers to personalise instruments in real time. Customers could visualise their orders in a virtual environment and make changes to designs, which are then immediately implemented by CNC machines.

Sustainable Development: CNC technologies, combined with other eco-friendly solutions, can contribute to more sustainable production practices. For example, the use of material recycling technologies and precise machining of production waste can reduce environmental impact and promote more sustainable growth in the music industry.

PREDICTIONS REGARDING CHANGES IN THE PRODUCTION AND SALE OF MUSICAL INSTRUMENTS

Concerns of Master Instrument Makers Regarding the Introduction of CNC Technology Based on interviews conducted.

The introduction of CNC technology into the production of master instruments raises several concerns among craftsmen who have long cultivated traditional craftsmanship methods. Master instruments, often handmade by experienced artisans, are valued for their uniqueness, high quality, and artistic value. Although CNC technology offers many benefits, such as precision, repeatability, and production efficiency, it also sparks controversy among those who fear its impact on traditional craftsmanship and the quality of instruments.

One of the main concerns regarding CNC is the potential loss of uniqueness and individuality in instruments. Master instrument makers, who specialise in handcrafting each component, value the ability to customise and personalize each instrument according to the client's wishes. Handcrafting allows for subtle modifications and adjustments that are difficult to achieve with CNC machines (Panufnik 2014**)**. With the fear that CNC technology could dominate the market, many craftsmen worry that their products may lose the unique character that results from handwork and the individual approach to each piece.

Another aspect that raises concerns is the potential loss of traditional craftsmanship skills. The creation of master instruments is a process that requires years of learning and practice. Skills such as precise wood cutting, detailed carving, and sound adjustment are passed down from generation to generation and are an integral part of cultural heritage (Petheric 1900). The introduction of CNC technology could lead to the marginalisation of these skills as production processes become more automated and less reliant on traditional craft techniques. As a result, there is a concern that not only skills but also the entire culture of craftsmanship associated with instrument-making may fade away.

Manufacturers also fear that CNC technology could lead to the homogenisation of products. With CNC machines operating based on programmed models, there is a risk that instruments could become too uniform and less varied. For many craftsmen and musicians who value the uniqueness and character of handmade instruments, such homogenisation is unacceptable. The uniqueness of each instrument, stemming from the craftsman's individual approach, is invaluable to many and is part of the artistic value of the instrument.

Another significant issue is the impact of CNC technology on work ethics and market structure. The introduction of CNC requires investment in modern machinery, which can be a barrier for small craft workshops that do not have large budgets. Companies involved in handcrafting instruments may be forced to change their business models or even close their operations if they are unable to compete with large manufacturers who can use CNC technology for mass production. These changes could lead to a reduction in the number of small, independent producers and a decrease in the diversity of the musical instrument market.

It is also worth noting that the introduction of CNC could bring changes to the work culture in craft workshops. Workers accustomed to manual labour may find it challenging to adapt to new technologies, leading to concerns about the loss of traditional jobs. Handcrafting instruments is not only a source of income for craftsmen but also an important part of their professional identity. Automation may alter the dynamic work environment that has been cultivated over the years, potentially affecting employee morale and job satisfaction (Hollaway 1972).

Finally, the issue of aesthetics and the artistic value of instruments produced using CNC also raises controversy. For many craftsmen and music enthusiasts, the aesthetics of an instrument are as important as its functionality. Handwork allows for the creation of an instrument that is not only functional but also aesthetically unique and reflects the individual

style of the maker. There is concern that instruments made with CNC may lack the same "soul" and personal character present in handmade products.

CONCLUSIONS AND SUMMARY

Precision and Repeatability: CNC offers unmatched precision and repeatability, which is crucial for producing high-quality musical instruments. This technology allows for the achievement of exact dimensions and shapes, which are essential for ensuring consistency and superior sound quality.

Material and Time Efficiency: CNC minimises material waste and shortens production time by efficiently utilising materials and automating machining processes. This leads to greater efficiency and reduced production costs.

Automation of Production: Integrating CNC into production processes allows for the automation of many stages, increasing productivity and enabling the production of a larger number of instruments in a shorter time. Automation also reduces the risk of human error.

Integration with 3D Printing: Combining CNC with 3D printing enables rapid prototyping, customisation, and the production of components with complex geometries, fostering innovation in instrument design.

Integration with Robotics: Robotics supports automation and precision finishing, enhancing production efficiency and instrument quality. Robots can also assist with complex assembly operations.

Technological Innovations: The development of artificial intelligence, new materials, and sustainable technologies may impact the future of instrument production, offering new opportunities for customisation, efficiency, and quality.

CONCLUSIONS AND RECOMMENDATIONS

Recommendations for the Introduction of CNC Technology in Musical Instrument Production:

Balancing Tradition with Modernity:

The introduction of CNC technology does not have to mean the complete abandonment of traditional craftsmanship. Instrument makers should strive to maintain a balance between manual skills and modern tools. A hybrid approach can be considered, where CNC is used for precision operations, such as cutting and milling, while manual elements remain an integral part of the production process.

Personalisation and Individuality:

CNC technology can be utilised to customize instruments according to the individual needs of customers. CNC is used to create unique shapes, decorations, and personalization while preserving the option for manual modifications so that the instruments retain their soul and character.

Education and Preservation of Tradition:

The introduction of CNC should not lead to the loss of traditional skills. Instrument makers should invest in educating young craftsmen to pass on knowledge and techniques related to instrument production. Workshops, training sessions, and collaboration with experienced masters can help preserve the craft heritage.

Research and Development:

Ongoing research into the application of CNC in instrument production opens opportunities for creating new body shapes and optimising sound. Collaboration with scientists, engineers, and artists can help harness the potential of CNC technology in creating musical instruments.

Transparency and Communication:

Informing customers about the production process and clearly explaining which elements are handmade and which are produced using CNC will build trust and demonstrate that technology does not replace tradition but complements it.

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Streszczenie: *Niniejsza praca analizuje integrację technologii CNC (Computer Numerical Control) w produkcji instrumentów muzycznych, koncentrując się na jej zaletach w zakresie precyzji, efektywności i personalizacji. Chociaż technologia CNC przynosi znaczące postępy, stawia również wyzwania przed tradycyjnym rzemiosłem, w tym potencjalną utratę unikalności i umiejętności rzemieślniczych. Praca zaleca zrównoważone podejście, łączące CNC z tradycyjnymi technikami, w celu usprawnienia produkcji przy jednoczesnym zachowaniu dziedzictwa kulturowego. Kładąc nacisk na edukację, badania i transparentną komunikację, praca ta opowiada się za rozważnym wdrożeniem technologii CNC, aby innowować w przemyśle muzycznym, zachowując jego rzemieślnicze korzenie.*

Słowa kluczowe: technologia CNC, produkcja instrumentów muzycznych, precyzyjna produkcja, hybrydowe metody produkcji

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