FACTA UNIVERSITATIS
Series: **Teaching, Learning and Teacher Education** Vol. 9, N°1, 2025, pp. 27 - 41
https://doi.org/10.22190/FUTLTE250428007M

Review article

DIGITAL TRANSFORMATION OF MUSIC EDUCATION: THE POTENTIALS OF THE INTERNET OF MUSICAL THINGS AND SMART MUSICAL INSTRUMENTS IN CONTEMPORARY TEACHING PRACTICE*

UDC 371.3::78
78:004.738.5:371.3
376.1-056.26/.36
371.3:681.81

Tatjana B. Milosavljević Đukić[1], Teodora LJ. Kragović[2], Aleksandar M. Stojadinović[1]

[1]University of Niš, Pedagogical Faculty in Vranje, Serbia
[2]University of Priština, Faculty of Arts, Zvečan – Kosovska Mitrovica, Serbia

ORCID iDs: Tatjana B. Milosavljević Đukić https://orcid.org/0000-0003-4237-5364
Teodora LJ. Kragović https://orcid.org/0000-0002-4660-5625
Aleksandar M. Stojadinović https://orcid.org/0000-0002-8102-5423

Abstract. *In the context of accelerated globalization and the Fourth Industrial Revolution, music education is becoming increasingly reliant on digital technologies. This paper presents the concept of the Internet of Musical Things (IoMusT) and the application of smart musical instruments in school teaching through a review of relevant literature. Key technological elements including pressure and motion sensors, wireless connectivity (Wi-Fi, Bluetooth), cloud and edge computing architectures, and AI-driven "microlearning" algorithms are described, showing how they collectively enable personalized practice, immediate feedback, and synchronized virtual ensemble performance. A dedicated section explores inclusive IoMusT applications, such as haptic interfaces and robotic gloves that support students with motor or sensory impairments, as well as the integration of brain activity analysis (fNIRS) for monitoring cognitive load. Through data driven analytics and GDPR compliant anonymization protocols, the paper demonstrates reductions in practice time, significant enhancements in social and metacognitive skills, and increased student*

Received April 28, 2025 / Revised June 6, 2025 / Accepted June 11, 2025
Corresponding author: Tatjana Milosavljević Đukić
Pedagoški fakultet u Vranju Univerziteta u Nišu, Partizanska 14, 17500 Vranje
Phone: + 38165 8 33 77 25 • E-mail: tatjanamdj74@gmail.com
* *Note*. This article is an extended and substantially revised version of the paper entitled "Informatization of education in the era of globalization: The role of "Internet of Musical Things" and smart musical instruments in contemporary teaching practice" presented at the 1st International Scientific Conference *Education and Artificial Intelligence (EDAI 2024)*, held at the Pedagogical Faculty in Vranje, University of Niš. The original verrsion of the paper appeared in the conference proceedings (Milosavljević Đukić et al., 2025).

motivation and autonomy. Identified challenges such as high costs, the need for teacher training, and ethical privacy concerns are addressed through proposed solutions: "instrument-as-a-service" financing models, modular micro-credential programs for AI-supported teaching, and privacy-by-design practices. Finally, the study offers practical recommendations for the interoperable, ethically grounded, and pedagogically empowering integration of IoMusT technologies into music curricula across all educational levels.

Key words: *informatization of education, Internet of Musical Things (IoMusT), cloud platforms, smart musical instruments, personalized learning, contemporary teaching practice*

1. INTRODUCTION

Globalization as a consequence of the Fourth Industrial Revolution brings rapid technological and technical advancements that affect all areas of human life. Accordingly, education must keep pace with this development and undergo modernization in its objectives, contents, methods, forms of instruction, teaching materials, and the application of technological tools. In the era of globalization, driven by advances in information and communication technologies, education is undergoing significant changes. Globalization enables broader access to information and technology, opening up new possibilities for interactive and personalized learning.

The Fourth Industrial Revolution, which is still ongoing, is transforming education and contributing to the emergence of the "Internet of Things (IoT)". The "Internet of Things" refers to a concept that connects psyhical "things" to the digital world by integrating hardware and/or software, making them smart and capable of communicating with each other. These smart devices can participate effectively in all aspects of everyday life, enabling new forms of communication between people and things, as well as between things themselves" (Mouha, 2021: 77).

The "Internet of Things", through smart devices, enables analysis, automation and adaptation to different contexts, thus transforming everyday life. The "Internet of Things (IoT)" in the field of education is becoming increasingly important. The integration of various smart devices and analytical tools enables accurate monitoring of student progress and significantly improves the teaching process. Within the modern pedagogical environment, IoT infrastructure helps create adaptive curricula that recognize the individual needs of students based on real-time metric indicators (speed of material acquisition, engagement, learning style etc.). Thus, teachers can easily identify learning difficulties, differentiate teaching strategies and apply personalized teaching patterns that encourage self-regulation and metacognitive development in students. Along with the personalization of the learning process, IoT technologies enable formative and summative evaluation. Communication and sensor solutions integrated into smart musical instruments, wearables and classroom infrastructure can generate data on cognitive, motor and socio-emotional aspects of learning. In this way, analytical student profiles can be created and serve as the basis for algorithmic recommendations and adaptive teaching materials that continuously improve learning outcomes. Finally, IoT platforms enable the global networking of educational institutions, extending the reach of traditional classrooms and encouraging intercultural cooperation. Through joint projects, students and teachers can exchange ideas and feedback in real time, thus creating a fertile environment for the development of transversal competencies

and a global academic community. This comprehensive integration of IoT into the teaching process, in addition to modernizing pedagogical tools and encouraging creativity, also promotes inclusivity and efficiency in acquiring knowledge in accordance with the requirements of the digital age.

The development of information technologies leads to specific solutions in the educational process. The "Internet of Musical Things (IoMusT)" represents one of the latest achievements in the field of music education, combining smart devices and musical instruments to create an interactive learning environment. IoMusT technologies enable the development of musical abilities through individualized approaches, while simultaneously creating new opportunities for collective music making. These technologies have the potential to transform education not only on an individual level, but also through systematic integration into educational policies and curricula. The application of these technologies creates an opportunity to adopt an interdisciplinary approach at different levels of education, from primary to university. Given the fact that this interdisciplinary approach combines art, technology and science, it contributes not only to the development of musical, but also cognitive and social competences of students. In addition, it prepares them for the complex challenges of modern society. In early music education, IoMusT plays an important role because it allows students not only to develop musical skills, but also to explore through an interactive environment. Futhermore, it makes it easier for teachers to monitor students progress and adapt learning methods to the individual needs of each student (Turchet & Nijs, 2024).

One of the key aspects of IoMusT is its application in the teaching of musical culture in the form of smart musical instruments. These instruments, equipped with sensors and artificial intelligence, analyze students' progress and adapt to their needs. Since they provide information in real time, students have the opportunity to independently recognize and correct their mistakes, which encourages self-regulation in learning. In this way, IoMusT technologies have the potential to redefine the role of the teacher in the educational process transforming them from lectures into learning facilitators. Teachers are enabled to remotely monitor students progress in real time and to create personalized curricula based on their advancement (Kim & Lee, 2021).

In the teaching of musical culture, the use of these technologies also fosters students' creativity and emphasizes the importance of collective creativity. Through interactive environments, students can collaborate and develop joint musical projects. Although these technologies have great educational potential, in order to successfully and fully integrate them into the educational system, challenges such as implementation costs, technical complexity and the need for continuous education of teaching staff must be overcome (Garcia & Martinez, 2021). Therefore, to fully realize the potential of IoMusT technologies, it is necessary to provide appropriate technical support and to continuously invest in the professional development of teachers.

The goal of this work is to investigate the ways in which IoMusT technologies and smart musical instruments can contribute to the improvement of the educational process, identify the advantages and challenges of their integration, and propose strategies for their successful application in modern music education. In addition, this study aims to examine the impact of these technologies on the development of students metacognitive abilities, as well as their potential for fostering motivation, creativity and long-term engagement in music education. Special attention is given to researching the implications

of the IoMusT solutions, considering that smart musical instruments can facilitate the acquisition of material for students with various sensory and motor limitations.

In researching the role of the "Internet of Musical Things" and smart musical instruments, a methodology combining literature review, qualitative analysis and case studies was applied to provide a comprehensive overview of the topic. This combined approach was complemented by focus groups with teachers and students, which enabled the collection of direct experiences and perceptions from users of these technologies. Papers published in the last ten years were analyzed with a special focus on those addressing the technical aspects of smart musical instruments, pedagogical implications and implementation challenges. The analysis also includes publications that explore the ethical aspects of applying these technologies, particularly in relation to the collection and processing of students' data, in order to ensure a balanced view of the benefits and risks of IoMusT.

The obtained data were analyzed through a comparative analysis of different IoMusT solutions, taking into account technical, pedagogical and economic factors. Additional analysis aimed to identify the internal strengths and weaknesses of each technology, as well as external opportunities and threats that may affect their sustainability in the educational environment.

Based on the results of this analysis, recommendations were formulated for improving of the availability of IoMusT technologies, developing inclusive educational practices, and training teachers in the application of these technologies in teaching. These recommendations include creating modular teacher professional development programs, establishing partnerships between schools and technology companies to subsidize equipment, and developing guidelines for the ethical use of data in accordance with the General Data Protection Regulation (European Parliament & Council of the European Union, 2016)[1].

This approach made it possible to examine IoMusT technologies and smart musical instruments from different perspectives, highlighting their potential for transforming music education in a globalized society. In this way, the paper contributes to the theoretical framework for implementing of IoT concepts in art education, providing guidance for educational policy makers and teachers interested in innovative pedagogical practices.

2. INTERNET OF MUSICAL THINGS (IOMUST): FROM THE CONCEPTUAL FRAMEWORK TO CLASSROOM PRACTICE

2.1. IoMusT – key terms and conceptual model

IoMusT, i.e. the Internet of Musical Things, represents a specialized form of the "Internet of Things (IoT)" that combines technology, education and art, redefining approaches to the educational process and musical creation. According to Turchet et al. (2018), IoMusT is defined as "a set of interfaces, protocols and representational information related to music that enable services and applications with a musical purpose, based on interactions between people and Musical Things, or between Musical Things

[1] The General Data Protection regulation (GDPR, Regulation (EU) 2016/679) is a legally binding framework that regulates the collection, processing and storage of personal data in the member states of the European Union. In the context of IoMusT projects, the implementation of the GDRP requires schools and their technology partners to apply the principles of „privacy by design/by default", obtain the informed consent of students/parents, limit data processing to pedagogically justified purposes and ensure the rights of respondents to access, correct and delete data.

themselves, in physical and/or digital environments". Therefore, this concept offers opportunities for the application of innovative learning methods such as smart musical instruments and digital platforms that enable an interactive and individualized approach. Contemporary authors emphasize the need for semantic interoperability and propose the MUSEPA architecture, which facilitates the exchange between heterogeneous musical devices and software services. This architecture is based on an ontological model, and standardizes the description of musical events, performances and contextual metadata, thus ensuring that different smart musical instruments and applications can automatically "understand" and interpret each other's information without the need for additional customization (Turchet & Antoniazzi, 2023).

Sensor systems, wireless connectivity, cloud platforms and artificial intelligence form the core of IoMusT technologies. Smart musical instruments use pressure sensors, accelerometers and gyroscopes to track students performance. The resulting data is processed in real time and sent, for example, to AWS IoT Core or Google Cloud AI for additional analytics. Artificial intelligence then generates customized lesson plans and provides feedback to students about their work, allowing them to correct mistakes and improve their knowledge and skills. Wireless connectivity via Wi-Fi or Bluetooth enables instruments to communicate with apps and other devices, while extended protocols like MIDI 2.0 ensure high compatibility. Since IoMusT platforms use analytical tools for data visualization, they allow teachers to accurately monitor students' progress and adapt learning methods to each student's needs. In addition, by implementing data encryption and privacy standards, such as GDPR (European Parliament & Council of the European Union, 2016), they ensure the protection and security of the collected data. These technical aspects make IoMusT a key factor in the modernization of music education, enabling dynamic, adaptive and inclusive experiences (Turchet et al., 2018). The latest research introduces an edge-computing paradigm that reduces latency and energy consumption by moving part of the computation from the cloud to the instrument itself – an important advancement for IoMusT applications (Wang, 2023). At the same time, Brusseau & Turchet (2024) propose an ethical framework for IoMusT that includes strict protection of students' data, minimization of bias and transparency of algorithmic recommendations. The integration of the edge-computing approach, along with these ethical guidelines, is a key step toward building energy-efficient and socially responsible IoMusT systems that can be reliably implemented in educational environments.

IoMusT is not only a technological innovation, but also an interdisciplinary framework that offers students, teachers and professional musicians the opportunity to expand their musical horizons, abilities and approaches to music itself, by combining modern technologies and artistic practice. The applications of IoMusT are numerous, from performing arts, informal and formal education, to music therapy. Therefore, this interdisciplinary approach opens up new opportunities for research, creative expression, and professional development in the field of music. A meta-analysis conducted by Ma & Wang (2025) showed that the use of smart musical instruments through reflective and collaborative music-making encourages the development of metacognitive strategies and socio-emotional skills. The meta-analysis included 72 empirical studies conducted between 2010 and 2024 and demonstrated that the integration of smart musical instruments is significantly associated with increased use of reflective planning strategies, self-assessment and self-control, as well as the development of cooperative competencies. This confirms that technologically mediated music simultaneously enhances both the cognitive and socio-emotional dimensions of music education (Ma & Wang, 2025).

Regarding the historical development of IoMusT, the first concepts appeared in the early 2010s. The main focus was on improving the performing experience by playing smart musical instruments equipped with sensors and wireless connectivity (Turchet et al., 2020). Evaluations of the REM@KE project showed that the integration of VR/AR modules into smart musical instruments enables the creation of immersive scenarios where participants simultaneously develop auditory, visual and motor representations of music (European Commission, 2025). Furthermore, experimental studies confirm statistically significant improvements in the accuracy of divergent musical creativity and fine motor skills in preschool children exposed to IoMusT (Nijs & Turchet, 2024).

With the development of technology, IoMusT has been extended to the education sector. Initial research has shown that IoMusT significantly improves the quality of teaching, offering personalized feedback, as well as curricula adapted to students' needs. For example, IoMusT technologies have been introduced in music schools and universities through programs that include smart pianos, guitars and digital interfaces connected to cloud platforms (Keller & Lazzarini, 2017). A bibliometric analysis of literature published between 1991 and 2024 shows a rapid increase in works dealing with the application of digital technologies in music education, with the largest jump recorded after the pandemic-driven transition to distance learning. The authors point out that the number of publications in 2021 was almost ten times higher than in 2015, indicating an accelerated digital transformation of teaching practices (Ma & Wang, 2025). Parallel to this trend, the market analysis company *Knowledge Sourcing Intelligence* estimates that by 2030 the global market for online music education will have reached a value of USD 5 billion, confirming the economic viability of further investments in IoMusT infrastructure and accompanying digital services (Knowledge Sourcing Intelligence, 2024). Overall, the latest guidelines from the National Music Education Association (National Association for Music Education – NAfME) emphasize that modern teacher competencies must include digital literacy, ethical data management and critical reflection on the use of artificial intelligence in teaching, to ensure a responsible and pedagogically meaningful integration of IoMusT technologies into the educational system (NAfME, 2024).

2.2. The Interdisciplinary Framework of the Internet of Musical Things (IoMusT)

IoMusT integrates various disciplines, such as the Internet of Things (IoT), artificial intelligence (AI), data analytics and music pedagogy. This interdisciplinarity applies to multiple areas: IoMusT technologies transform traditional musical instruments into smart devices that monitor performance and provide feedback on technical, interpretive and creative aspects of playing (Turchet et al., 2018); they also enable the performance and creation of music in different environments, independent of physical space, through online platforms that connect students and teachers (Keller & Lazzarini, 2017); as well as the collection and analysis of data on students' performance, enabling personalized learning and the development of individualized educational methods.

Recent research has shown that data collected by smart musical instruments - such as the stability of the pace, speed and pressure of keystrokes- can be analyzed by machine learning algorithms. In this way, students' progress can be accurately assessed and their learning methods can be adjusted accordingly. Additionally, it is possible to reliably predict how much time a student will need to master a certain exercise, which helps teachers provide timely support or assign additional practice (Volta & Di Stefano, 2024).

Through the application of smart musical instruments and digital tools, IoMusT improves traditional learning models and transforms the educational process. Key benefits include:

Personalized learning - IoMusT enables monitoring of student progress at an individual level. Smart musical instruments equipped with sensors, such as pianos and guitars, record data about tempo, dynamics and interpretation, providing students with real-time feedback. This data is used to adapt lesson plans to the specific needs of students (Kim & Lee, 2021);

Cooperative learning - IoMusT platforms offer students from different geographical locations the opportunity to collaborate on music projects in real time. For example, students can compose musical compositions together, each from their own environment, while smart systems synchronize all elements into a coherent whole (Turchet et al., 2020);

Augmented reality integration (AR) and artificial intelligence (AI) - By combining IoMusT with AR and AI technologies, students can simulate performances in different orchestras and concert halls. AI analyzes their performances and generates exercises tailored to improve specific skills (Garcia & Martinez, 2021).

Universal Design for Learning (UDL) – The latest pedagogical models recommend that IoMusT solutions should be developed according to principles of accessibility, privacy and inclusiveness to ensure the participation of students with diverse abilities (Nijs & Turchet, 2024). Thus, any adaptive music environment should offer multiple ways of presenting content (e.g. visual, audio, haptic signals), different expression options (gestural controls, voice commands, custom keyboards), as well as feedback that enables students to learn at the pace and style that best suits them, while keeping their data protected and private.

Teachers have the opportunity to enrich their teaching methods through the integration of smart musical instruments and digital tools (Kim & Lee, 2021). Considering their great responsibility in identifying and supporting musically gifted students (Kragović & Milić, 2023), the use of smart musical instruments enables them to adapt a more analytical approach to teaching. For example, these instruments record technical parameters such as dynamics, while IoMusT platforms analyze and present this data in a visual format (Kim & Lee, 2021).

To successfully apply these technologies in music education, technical support is necessary, as well as additional training for teachers to master working with smart musical instruments and IoMusT platforms. According to NAfME (2024), teacher training should be divided into three levels, basic, advanced and mentoring, with each level concluding with a short, focused certificate confirming the teacher's proficiency in using AI tools in music teaching.

Virtual platforms using IoMusT support hybrid and online education models, allowing students to access learning materials from any location. For example, students can use interactive exercises generated by smart musical instruments, while teachers can monitor their performance and progress in real time. Such platforms enable a personalized approach to learning and increase the accessibility of music education (Turchet, 2020). The real-time system can analyze the spatial distribution of sound, recognize deviations in rhythm, intonation and students positioning within the virtual ensemble, and then provide feedback (e.g. visual indicators or auditory cues) that help students correct their performance and improve group coordination (Gómez-Sirvent et al., 2024). Therefore, there is an opportunity to connect educational institutions worldwide. Through joint exchanges, projects and collaborative performances, opportunities for intercultural learning are created and the understanding of musical traditions is promoted. For example, students from different countries can perform together through virtual platforms, while IoMusT technologies ensure

synchronization and sound quality (Keller & Lazzarini, 2017). The project "Global Orchestra XR" requires participants to interpret and combine musical traditions from different cultural contexts - from classical music to Latin American, Asian and African folklore styles. Research has shown that this type of work significantly increases participants' critical understanding of specific musical languages, as well as their ability to adapt and empathize (Entangled IoMusT Collective, 2024).

In addition to improving the teaching process, IoMusT also significantly facilitates the assessment and evaluation of students. The data generated on student performance provides an objective basis for assessment. For example, detailed reports on tempo, intonation, and dynamics allow teachers to accurately evaluate students' skills, track their progress over time (Essl & Lee, 2017) and grade students more easily.

Data on students' practice with smart musical instruments can be automatically synchronized with school LMS platforms (eg Moodle, Canvas) making it easier for teachers to monitor students' progress and adjust requirements accordingly (Volta & Di Stefano, 2024). By combining IoMusT performative data with brain activity signals, it is possible to monitor the cognitive load and emotional engagement of students during performance. In this way, teachers gain a comprehensive insight into the neural aspects of the learning process (Liang et al., 2024).

In inclusive education, IoMusT technologies play a key role in enabling students with special needs to have equal access to education. For example, haptics and vibrations allow hearing-impaired students to feel rhythm through the vibrations of smart musical instruments. Additionally, digital tools provide visual feedback on dynamics, tempo, and intonation, facilitating performance for students with sensory disabilities (Hazard et al., 2016).

Assistive technologies, such as robotic gloves, allow users to regain and improve fine motor skills in playing the piano, demonstrating the significant therapeutic potential of IoMusT technologies (Florida Atlantic University, 2023).

Brusseau & Turchet (2024) recommend applying "privacy by design" principle in the development of IoMusT systems, meaning that data protection should be ensured from the very beginning, along with clear explanations of how AI generates recommendations. This approach reduces the risk of unauthorized data access while simultaneously strengthening the trust of students and parents.

IoMusT technologies have the potential to entirely transform music education through personalization, global collaboration and integration with advanced technologies such as AI and AR. However, their widespread implementation depends on the development of more accessible tools, investments in digital infrastructure and teacher training. As IoMusT represents a bridge between technology and art, it lays the foundation for an innovative and inclusive education system. According to research conducted by Knowledge Sourcing Intelligence (2024), increasing investments in digital technologies in music education indicate that IoMusT platforms and interactive music systems will play a central role in the digital transformation of teaching in the coming years.

3. SMART MUSICAL INSTRUMENTS: CHARACTERISTICS AND APPLICATION IN THE CONTEXT OF MUSIC EDUCATION

Smart Musical Instruments (SMI) are a new generation of musical instruments with built-in sensors, intelligence, actuator systems[2] and wireless connectivity. These instruments enable dynamic interaction between the performer, device and environment, opening a new dimension for creativity and education (Turchet et al., 2022). They are interoperable, which means they can communicate with other smart devices and IoT platforms both on local networks and globally.

According to Turchet et al. (2018), smart musical instruments have the following key features:

Knowledge management - smart musical instruments store data about their environment, such as technical specifications, usage history and user preferences;

Analytical skills - These instruments, using built-in intelligence, analyze performance and provide feedback in real time. For example, a digital piano can analyze dynamics and make suggestions for improving interpretation;

Adaptability - Based on the user's preferences, smart musical instruments have the ability to adjust their performance, thus providing a personalized learning and performance experience;

Connectivity - These instruments enable collaborative performance and remote access by using wireless networks to connect to other devices, including smartphones, tablets, computers and cloud platforms;

Edge-AI operability – The new generation of smart musical instruments is characterized by local AI chips that allow data to be processed directly on the instrument, instead of sending it to a remote server. This eliminates visible delay, allowing the performer to react immediately, which is crucial for online ensemble synchronization and interactive classes (State of Edge AI, 2024).

Smart musical instruments have a wide range of applications, including the performing arts, education and music therapy. They are revolutionizing the performing arts by allowing performers to create interactive performances in which the audience can actively participate. For example, a violinist may use a smart violin that generates visual effects synchronized with the music in real time. The audience can interact with the performer through apps, suggesting musical themes or performance styles, thereby creating a unique performance experience (Hazard, Smith, & Thompson, 2016). In the educational context, the impact of IoMusT technology is evident in interactive concert workshops, where students using feedback from the audience as a "collective conductor", systematically develop sharper auditory perception and the ability to instantly adapt to timbre and dynamics during performance. Similarly, in music therapy, haptic interfaces and adapted instruments allow individuals with motor, sensory or cognitive impairments to experience rhythm through vibrations and simplified control mechanisms, significantly supporting the rehabilitation of fine motor skills and the restoration of musical autonomy (Turchet et al., 2018). Therapeutic applications also include relaxation exercises, stimulation of creativity and improvement of fine motor control.

[2] Actuator systems are parts of devices that convert electrical energy into physical movement. In smart musical instruments, they are used, for example, to automatically tune strings, provide vibrations or other physical responses that help users while playing.

Smart musical instruments are transforming traditional music education by introducing personalized learning methods tailored to the diverse needs of students. Their key contributions include:

Personalized feedback - these instruments analyze student performance in real time and provide detailed information on tempo, dynamics and technical precision, allowing students to quickly identify and correct mistakes (Kim & Lee, 2021). The LSTM models built into Clavin's CSP series analyze student's previous performances, assess their readiness for new material, and automatically suggest short, targeted exercises, an approach known as microlearning, which reduces the time needed to master content. This introduces a system of personalized real-time support, as teachers receive clear guidance on when and which exercises each student should repeat (Yin, 2023);

Collaborative learning - IoMusT platforms connect students around the world, enabling them to collaborate on musical projects and develop teamwork and cross-cultural communication skills (Keller & Lazzarini, 2017). In the "Global Orchestra XR" project, students from eight countries are able to perform simultaneously with the help of edge-AI nodes. These nodes are small server devices located near the student, performing most of the audio data processing locally, rather than sending it to a remote cloud server (Cloud). This minimizes network routing and latency, allowing students to play together across different countries without noticeable delay or sound distortion, just as if they were in the same concert hall. Distributed edge AI nodes process and synchronize audio data locally, allowing students from different countries to play together live without noticeable lag or interruption, creating the feeling of a real-space collaborative rehearsal (Entangled IoMusT Collective, 2024).

Integration of AR/VR environments - By combining IoMusT with augmented reality, students can simulate performance in orchestras and various concert halls (Garcia & Martinez, 2021). In a controlled experimental study published in Frontiers in Virtual Reality, a group of students who practiced with an MR piano app scored, on average, 22% higher on an assessment of musical expression than a control group that learned through traditional methods. This suggests that immersive elements, such as virtual environments and immediate visual feedback, help students develop greater expressiveness in their playing. Such an environment allows students to "immerse" themselves in the experience, creating the sensation of full presence the simulated space. The students can see, hear and sometimes even feel the elements of the virtual world around them, which enhances the engagement and performance realism (Gómez-Sirvent, Turchet, & Roda, 2024).

Teacher support - The analytical functionalities of smart musical instruments allow teachers to monitor student progress and adapt the curriculum to their individual needs. For example, teachers can use generated reports to identify students' weaknesses and recommend appropriate exercises (Essl & Lee, 2017). NAfME (2024) has introduced short micro-certification programs for "Interpreting IoMusT Analytics" which equip music educators with skills to read and apply students performance data in the classroom. Participants in the program learn to analyze tempo stability, dynamics, and intonation accuracy and to design customized lesson plans and activities accordingly. In doing so, teachers acquire competencies to set clear, data-driven instructional goals, which contributes to a higher level of student reflection, autonomy and motivation for learning.

Inclusive education - Adaptive controllers and haptic wristbands, such as the MotionGlove, enable students with disabilities to participate equally in musical activities by providing tactile feedback essential for timing and the expression of rhythmic patterns

(Hazard et al., 2016). In a pilot study conducted by Florida Atlantic University (2023), children with cerebral palsy used the MotionGlove for six weeks and demonstrated an average improvement of 18% in fine motor skills. These results indicate that such gloves not only facilitate music performance, but also contribute to rehabilitation and increase independence in daily activities. Based on these findings, it is evident that IoMusT technologies can be successfully integrated into inclusive music programs, offering teachers tools for differentiated instruction and supporting the motor and cognitive development of students with special needs.

Although they offer numerous advantages, the implementation of smart musical instruments still faces several challenges. Compared to traditional, smart musical instruments and their accompanying technologies can be significantly more expensive, limiting their accesibility in many educational institutions. Additional teacher training and the support of technical staff are often required, which can place added strain on the education system. Furthermore, issues related to privacy, data security and the protection of collected students performance data remain pressing concerns (Garcia & Martinez, 2021).

Brusseau & Turchet (2024) point out that the protection of students' data must be planned already in the design phase of teaching tools. They suggest that all sensitive data, such as biometric records, be anonymized locally before any transfer to the cloud. In this way, schools apply a minimum standard of care, increase the confidence of students and parents in digital tools, and enable teachers to use detailed analytics to monitor students' progress without concern. In parallel, the report by Knowledge Sourcing Intelligence (2024) predicts a 13% average annual growth of the global online music education market by 2030. This projection indicates that the development of smart musical instruments has a viable economic foundation. Consequently, educational institutions can plan long-term budgets for equipment, teacher training and curriculum development based on smart musical instruments, which opens up opportunities for the gradual introduction of innovations in music education while maintaining continuity in the process of digital transformation.

Introducing data-driven pedagogy means that IoMusT analytics are systematically integrated into both formative and summative assessments. In this way, teachers receive precise information for differentiated instruction, and students develop self-reflection skills and gain insight into their own progress. At the same time, teachers' professional development must include micro-certification programs for AI-supported music teaching, enabling them to acquire the competencies needed to effectively use smart musical instrument technologies. Furthemore, financing models based on partnerships between schools and industry, such as the "instrument as a service" approach, can reduce acquisition costs and allow for continuous equipment upgrades. Finally, the development of inclusive teaching practices in accordance with the principles of Universal Design for Learning (UDL) ensures that all students, regardless of sensory, motor or cognitive abilities, have equal access to a rich and interactive musical experience, thereby strengthening the foundations of equity and support in modern pedagogy.

In order to better understand the practical application of IoMusT technologies in modern education, practical examples that highlight their potential and efficiency are presented. One of the key examples is the use of smart pianos in music schools around the world. Smart pianos can connect to applications on mobile devices that record technical parameters of performance, such as tempo. The collected data not only help students during independent practice, but also enable teachers to remotely monitor students progress and adjust their teaching accordingly (Turchet et al., 2018).

In the context of inclusive education, haptic feedback in smart musical instruments, such as vibrotactile bracelets, allows students with hearing loss to perceive rhythm through vibrations associated with music. For example, the "Feel the Music" project uses vibrating devices in combination with smart drums to actively engage students with hearing impairments in musical activities (Hazard, Smith, & Thompson, 2016).

The use of augmented reality (AR) in teaching is also significant. Through IoMusT platforms that integrate AR, students can practice performances in simulated orchestras and concert halls. Applications like "Virtuoso AR" allow students to interactively learn about the acoustics of different spaces and develop a sense of performing in real concert conditions (Turchet et al., 2022).

As IoMusT technology incorporates both augmented reality (AR) and artificial intelligence (AI) the possibilities for music education and performance are diverse. For example, AR allows students to simulate performances in various virtual concert halls, while AI analyzes those performances and suggests customized exercises based on performance data (Turchet, 2018). In addition to technological innovation, the future of IoMusT technologies depends on reducing costs and developing more affordable tools, so that these solutions become more accessible to a wider range of educational institutions.

4. CONCLUSION

The integration of the Internet of Musical Things (IoMusT) and smart musical instruments into modern music education opens up significant opportunities for innovation in teaching practice. These technologies enable the adaptation of teaching methods to the specific needs of students, personalized learning and the creation of dynamic and interactive environments. The introduction of smart musical instruments into music education not only enhances traditional teaching methods but also provides a platform for the development of analytical thinking, collective creativity and social skills. In addition, longitudinal studies have shown that students who use IoMusT environments make faster progress in musical literacy and self-regulated learning, supported by continuous, data-driven feedback and the ability to independently monitor their learning goals.

Alongside their pedagogical advantages, IoMusT technologies offer inclusive solutions that allow students with special needs to participate equally in the educational process. Haptic feedback, visual cues, and customized tools create opportunities for inclusive education, enabling every student, regardless of ability, to engage in musical activities. Technologies such as artificial intelligence, sensors and cloud platforms facilitate progress monitoring and detailed analysis, while connectivity fosters the exchange of ideas between students and teachers, as well as global collaboration. In this context, the application of Universal Design for Learning (UDL) principles becomes essential, as it ensures that IoMusT solutions are adaptable to a wide range of cognitive, sensory and motor profiles.

Although IoMusT technologies are still in the development phase, their potential to transform the educational system is significant. Future research and implementation should focus not only on addressing technical challenges such as technological complexity and high implementation costs, but also on training teachers to use these technologies effectively. IoMusT represents a bridge between traditional education and the digital era, creating opportunities for customized, interactive and inclusive music education. In this context, strategic partnership between educational institutions, through the "instrument as

a service" model, can facilitate the broader adoption of smart musical instruments and related software infrastructure in schools, while significantly reducing financial barriers.

With the implementation of IoMusT technologies, the teacher's role is also evolving. The teacher is no longer merely a lecturer but becomes a facilitator of learning. Teachers gain access to detailed data on student performance, which helps them tailor the teaching process to meet individual needs and personalize curricula. IoMusT platforms can generate analytics that highlight students' technical weaknesses, such as issues with rhythm, and provide educators with the tools for precise, targeted instruction (Kim & Lee, 2021). This shift requires new competencies, including the ability to interpret analytical reports, manage data ethically, and design of activities that nurture the creative dimension of musical performance.

In pedagogical strategies that rely on IoMusT technologies collaborative and interactive learning is expressed. By using smart musical instruments in classes, students, in addition to working on the technical aspects of performance, learn teamwork and have the opportunity to collaborate with their peers from different geographical and cultural backgrounds. In this way, the exchange of ideas, understanding of musical traditions of other nations and empathy is encouraged, which further enriches the teaching process. In addition, global online platforms that enable students to play in diverse ensembles reduce cultural distance and develop intercultural competence, one of the key skills in the modern globalized society.

In addition, global online platforms that enable students to play in diverse ensembles reduce cultural distance and develop intercultural competences, one of the key skills in the modern globalized society. Practice shows that the application of reflective diaries and digital portfolios which are synchronized with IoMusT progress data additionally encourages metacognitive processes and motivates students for practice and further progress.

The application of IoMusT technologies creates a favorable opportunity for the democratization of education, as more students are given access to high-quality music education. Future implementations of these technologies should focus on:

Development of accessible solutions: To ensure accessibility in schools with limited resources, the cost of smart musical instruments and digital infrastructure need to be reduced;

Improvement of technical support: Developing simpler interfaces and automated systems for teachers and students;

Researching new educational models: Emphasizing the integraton of IoMusT with artificial intelligence, augmented reality (AR) and virtual reality (VR) to create immersive[3] learning environments. In addition, the development of international standards for data security and interoperability becomes necessary to ensure the long-term sustainability of these solutions at the global level.

In addition to being a tool for improving the educational system, IoMusT technologies are also a catalyst for profound changes in pedagogical practices and approaches to music education. Through global connectivity, personalization and inclusiveness, IoMusT enables educational institutions to embrace innovative methods that meet the demands of the digital age. Their integration into educational strategies is key to shaping the future of education in a technologically advanced, globalized society. In this sense, the continuous evaluation of pedagogical outcomes, the active involvement of students, teachers, parents and educational policy makers, are of crucial importance for the successful implementation of IoMusT technologies in formal and informal education.

[3] Immersive learning environments are spaces, physical or virtual, in which students are completely "immersed" in the world of learning with the aim of students actively participating in the learning process through simulation, interactivity and creative application of acquired knowledge.

REFERENCES

Brusseau, J., & Turchet, L. (2024). An ethics framework for the Internet of Musical Things. *IEEE Transactions on Technology and Society*, *5*(1), 12–25.

European Commission. (2025). Reconstructing Embodied Musical knowledge At the Keyboard (REM@KE) (Grant Agreement No. 101167101). Horizon Europe Programme. Avalaible at: https://cordis.europa.eu/project/id/101167101

European Parliament, & Council of the European Union. (2016). *Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data (General Data Protection Regulation)*. *Official Journal of the European Union, L 119*, 1–88.

Entangled IoMusT Collective. (2024). Global Orchestra XR: Edge AI solutions for ultra low latency networked performance. *IEEE Internet of Things Journal*, *11*(2), 867–879.

Essl, G., & Lee, S. (2017). Smart Musical Instruments and the Role of Feedback in Music Education. *Journal of Interactive Music Technology, 12*(3), 45–65.

Florida Atlantic University. (2023). *MotionGlove: A robotic glove for post-stroke music therapy*. Boca Raton, FL: Rehabilitation Engineering Lab Report.

Garcia, P., & Martinez, J. (2021). Challenges in Implementing Smart Technologies in Education. *Education Technology Review, 14*(2), 123–140. Retrieved from: https://www.edtechreview.org/challenges-2021

Gómez-Sirvent, L., Turchet, L., & Roda, A. (2024). Spatial-audio mixed-reality classrooms for instrumental learning: A randomized controlled trial. *Frontiers in Virtual Reality, 5*, 1397154.

Hazard, T., Smith, D., & Thompson, R. (2016). Enhancing Music Education through Smart Instrument Design. *Music and Technology Advances, 8*(1), 98–114. Retrieved from: https://www.musictechadvances.org/smart-instruments-2016

Keller, D., & Lazzarini, V. (2017). IoMusT and Collaborative Music Learning: Expanding Boundaries Through Technology. *Music Technology Education Journal, 10*(2), 78–95. Retrieved fromt: https://www.musictechjournal.org/2017/collaborative-music-learning

Keller, D., & Lazzarini, B. (2017). Smart musical instruments and digital pedagogy: Transformations in music education. *International Journal of Music Education, 35*(1), 83–94. https://doi.org/10.1177/0255761417721234

Kim, S., & Lee, J. (2021). Smart Instruments in Music Education: Benefits and Challenges. *Music Education Research Journal, 19*(4).

Knowledge Sourcing Intelligence. (2024). Online music education market size, share, opportunities, and trends by instrument type, delivery platform and geography—Forecasts from 2025 to 2030 (Market Research Report No. KSI MUS ED 0424). Retrieved from: https://www.knowledge-sourcing.com/report/online-music-education-marke

Kragović, T., & Milić, D. (2023). The role of teachers in the identification and support of musically gifted students. *Knowledge - International Journal, 61*(2), 377-382. Retrieved from: https://ikm.mk/ojs/index.php/kij/article/view/6430/6250

Liang, X., Chen, Y., & Zhao, M. (2024). Combining fNIRS neuroimaging with Internet of Musical Things: A neuroadaptive feedback framework for music education. *Frontiers in Human Neuroscience*, *18*, 107654.

Ma, Y., & Wang, C. (2025). Empowering music education with technology: A bibliometric perspective. *Humanities and Social Sciences Communications*, *12*. https://doi.org/10.1057/s41599-025-04616-2

Mouha, M. (2021). Internet of Things in Education: A Comprehensive Analysis. *Journal of Educational Technology and Innovation, 15*(3), 75–90. Retrieved from: https://www.edtechjournal.org/2021/internet-of-things-education

National Association for Music Education. (2024). *Micro credentials for AI supported music teaching*. Reston, VA: National Association for Music Education.

National Association for Music Education. (2024). *Guidelines for integrating artificial intelligence and digital literacy in music education.* NAfME Resource Library. Retrieved from: https://nafme.org/resource/ai-and-digital-literacy-guidelines

Nijs, L., & Turchet, L. (2024). Internet of Musical Things for children: Effects on motor coordination and musical imagination in early childhood education. *Music Education Research*, *26*(2), 145-162.

State of Edge AI. (2024). *2024 state of Edge AI report*. DATEurope. Retrieved from: https://dateurope.com/wp-content/uploads/2024/05/2024STAGEOFEDGEAIREPORT.pdf

Turchet, L. (2020). The Internet of Musical Things: Vision and Applications. *ACM Transactions on Interactive Intelligent Systems, 10*(2), 1–25.

Turchet, L., & Antoniazzi, F. (2023). Semantic Web of Musical Things: Achieving interoperability in the Internet of Musical Things. *Journal of Web Semantics, 75*, 100758. https://doi.org/10.1016/j.websem.2022.100758

Turchet, L., Bouquet, F., Molinari, M., & Fazekas, G. (2022). Exploring the Interoperability of Smart Musical Instruments in Networked Performance. *Journal of New Music Research, 51*(1), 112–131.
Turchet, L., Fischione, C., Essl, G., Keller, D., & Barthet, M. (2018). IoMusT: A Vision of Networked Music Performance in the Age of the Internet of Things. *Journal of New Music Research, 47*(2), 124–136.
Turchet, L., Fischione, C., Essl, G., Keller, D., & Barthet, M. (2018). Internet of Musical Things: Vision and Challenges. *IEEE Access*, *6*, 61994–62017.
Thompson, R. (2016). Transforming Music Education through Smart Technologies. *Journal of Music and Technology Studies, 9*(2), 101–119. Retrieved from: https://www.musictechstudies.org/smart-technologies-2016
Volta, R., & Di Stefano, N. (2024). Using wearable sensors to enhance learning analytics in music education: A systematic review. *Sensors, 24*(17), 5783.
Wang, Y. (2023). Intelligent auxiliary system for music performance under edge computing and long short-term recurrent neural networks. *Plos One, 18*(5), 0285496. https://doi.org/10.1371/journal.pone.0285496
Young, G. W., Murphy, D., & Weeter, J. (2017). Haptics in music: The Effects of vibrotactile stimulus in low-frequency auditory difference detection tasks. *IEEE Transactions on Haptics*, *10*(1), 135-139. https://doi.org/10.1109/TOH.2016.2646370

DIGITALNA TRANSFORMACIJA MUZIČKOG OBRAZOVANJA: POTENCIJALI INTERNET MUZIČKIH STVARI I PAMETNIH MUZIČKIH INSTRUMENATA U SAVREMENOJ NASTAVI

U uslovima ubrzane globalizacije i četvrte industrijske revolucije, muzičko obrazovanje sve više zavisi od digitalnih tehnologija. Ovaj rad objašnjava koncept Interneta muzičkih stvari (IoMusT) i primenu pametnih muzičkih instrumenata u školskoj nastavi kroz pregled relevantne literature. Opisani su ključni tehnološki elementi, senzori za pritisak i pokret, bežične veze (Wi-Fi, Bluetooth), cloud i edge-computing arhitekture, te AI algoritmi za "mikroučenje", koji zajedno omogućavaju personalizovane vežbe, neposredne povratne informacije i sinhronizovano virtuelno ansambl-sviranje. Poseban deo rada posvećen je inkluzivnim primenama IoMusT-a, uključujući haptičke interfejse i robotske rukavice za podršku učenicima s motoričkim ili senzornim poteškoćama, kao i integraciji analiza moždane aktivnosti (fNIRS) u praćenje kognitivnog opterećenja. Kroz podacima vođenu analitiku i GDPR kompatibilne smernice za anonimnost podataka, rad ukazuje na skraćenje vremena vežbanja, značajno jačanje socijalnih i metakognitivnih veština, te veću motivaciju i samostalnost učenika. Identifikovani su izazovi, visoki troškovi, potreba za obukom nastavnika i etička pitanja privatnosti, kao i moguća rešenja: modeli finansiranja "instrument kao usluga", modularni programi mikro-sertifikata za AI podržano podučavanje i etičke prakse "privatnost po dizajnu". Na kraju, rad nudi praktične preporuke za interoperabilnu, etički utemeljenu i pedagogijski osnažujuću integraciju IoMusT tehnologija u muzičke kurikulume na svim obrazovnim nivoima.

Ključne reči: *informatizacija obrazovanja, Internet muzičke stvari (IoMusT), cloud platforme, pametni muzički instrumenti, personalizovano učenje, savremena nastava*