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Technical note

Acoustic characteristics of UNESCO listed wooden churches in Southern Poland: A comparative study between Orthodox and Catholic churches

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A B S T R A C T

The article provides a comprehensive comparative analysis of the acoustics of wooden Catholic and Orthodox churches in Poland, all of which are UNESCO World Heritage sites. Using data collected as part of the "Multisensory UNESCO" digitalization project, evaluation of acoustic parameters such as reverberation time, speech and music clarity and others in each church was provided. The findings reveal that Catholic churches exhibit more acoustic diversity than Orthodox ones, and the acoustic characteristics of these spaces reflect not only their physical attributes but also their cultural and liturgical contexts. The research underscores the importance of preserving these unique acoustic environments, which contribute significantly to the historical and cultural value of these churches.

1. Introduction

The UNESCO World Heritage List includes both natural and cultural sites that have been deemed to be of exceptional value to humanity [1]. In particular, the cultural sites on the list are often recognized for their significance in terms of material heritage, which refers to tangible objects, buildings, and landscapes that have cultural or historical importance. This material heritage can provide important insights into past societies, technologies, and artistic traditions. The inclusion of a site on the UNESCO World Heritage List can bring international attention and funding for its preservation and management, and also raises awareness of the need to protect these unique cultural treasures for future generations [1]. The wooden Catholic Churches (CC) and Orthodox Churches (OC) in Southern Poland are a testament to the rich cultural and religious history of the region [2]. Dating back to the medieval period, these churches were constructed by skilled craftsmen using traditional techniques and materials, such as timber frames and shingles made of split wood. The region became a hub of wooden church construction during the 16th and 17th centuries, as the Counter-Reformation sparked a renewed interest in Catholic architecture. The churches in this region also exhibit a blend of Gothic, Renaissance, and Baroque architectural styles. These churches not only provide important insights into the history of Christianity in Poland, but also showcase the artistic and architectural achievements of the region's craftsmen. Some prominent examples of the wooden UNESCO churches are shown in Fig. 1.

Despite importance of the sacred wooden architecture inscribed at UNSCO list, little research has been conducted on the acoustics of these churches, especially in comparison to their stone counterparts. In this research paper, the main aim is to explore the acoustics of these unique structures and analyze the factors that contribute to their distinct timbre. The second important goal is to compare acoustics of the wooden UNESCO Orthodox and Catholic churches in Poland since they share many similarities, as both have been built using traditional materials and techniques. However, there are also some key differences between the two types of churches. One notable difference is in their architectural styles. While both types of churches feature timber frame construction, OC tend to have a more distinctively Eastern European style, with steeply pitched roofs, onion-shaped domes, and ornate, brightly painted iconostases separating the nave from the sanctuary [3]. CC, on the other hand, often incorporate Gothic, Renaissance, and Baroque elements, such as pointed arches, sculptural details, and decorative frescoes. Another difference is in their religious practices. OC often follow the Byzantine liturgical tradition, which emphasizes the use of icons, incense, and chant. CC, by contrast, have a more diverse range of liturgical practices, influenced by the Church's history and geography. Despite these differences, both types of wooden churches in Poland have played a significant role in the country's cultural and religious history, and continue to be important landmarks that draw visitors from around the world [2]. The current research is a part of the Pełni Kultury foundation project called "Multisensory UNESCO. Digitization of the cultural

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Fig. 1. Example photos of selected UNESCO wooden churches: a) Church of St. Michael the Archangel in Brunary, b) Church of St. Philip and St. James the Apostles in Sękowa, c) Church of St. Paraskeva in Kwiaton.

Fig. 2. Illustration of the laser scanning process and subsequent data postprocessing applied to the Church of All Saints in Blizne.

heritage (. . .)" https://digitalunesco.pl/. The project entails a comprehensive suite of digitalization and technical tasks, including:

- Laser scanning of objects and buildings (Fig. 2), creating animations containing audio descriptions for the visually impaired and subtitles for the deaf people.
- Detailed acoustic research using spatial impulse responses and the ambisonic technique.
- Texts on the intangible cultural heritage of the buildings.
- Audio descriptions of selected objects.
- Educational events.

As part of the UNESCO Multisensory project, comprehensive acoustic evaluations were carried out on churches. The data collected included numerical values such as reverberation time, speech and music clarity, speech intelligibility, sound spatiality, and others. This data can be used in virtualization and auralization. The visual animations of the effects of the work are available on the YouTube channel of the Pełni Kultury Foundation [4], and the measured Spatial Impulse Responses (SIRs) analyzed in the current paper are available for download in several formats, as well as audio recordings in ambisonics connected with the project [5]. It should be emphasized that the acoustic initiatives implemented under this project are an example of good practice, as most of architecture digitalization activities tend to overlook the importance of sound. The topic of Orthodox church acoustics in general is rarely present in the literature. The few published works, e.g. [6], [7], discuss Balkan Orthodox churches. Work of Elicio and Martellotta [8] describes in detail the acoustics of the Orthodox Church of San Nicola (also known as the "Russian Church") in Bari, but it also includes an interesting set of the main characteristics of selected Orthodox churches in Russia and Greece. The previous work published in Archives of Acoustics by the current paper author [9] covers the subject of acoustics of Orthodox churches in Poland in general. It includes the analysis of St Basil the Great Orthodox Church in Konieczna which is an example of wooden orthodox church but is not enlisted in UNESCO List. Furthermore, the work of [10] shows the Index assessment of the acoustics of chosen Orthodox churches in Poland. The index method for the acoustic assessment of Orthodox churches was adapted from a method dedicated to Roman Catholic churches. In general, the topic of Catholic churches is exploited by various authors, among others: [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21] and [22]. These works cover a very broad spectrum of Catholic church acoustics. They include analysis of several churches mostly in Italy and Spain, together with focus on research methodology in sacral buildings (among others: [15], [13]. The current paper focuses on the acoustic survey of Polish Catholic and Orthodox wooden churches that are part of the UNESCO World Heritage Sites, to understand how their specific architectural features and materials influence their acoustic properties. The main goal is to preserve and document the unique acoustic heritage of these sites, contributing to the broader understanding of the interaction between architectural design and cultural practices in religious structures. The second section provides detailed descriptions of the architectural features, construction materials, and historical context of the wooden Catholic and Orthodox Churches in Poland that were studied. Third section outlines the methodology used for collecting and analyzing the acoustic data from the churches, including the equipment used and the specific parameters measured. The next section presents the results of the acoustic measurements, including comparisons between Catholic and Orthodox Churches, and a discussion of how these results relate to the architectural features and liturgical practices of the churches. The Discussion, Summary, and Conclusion sections encapsulate the primary findings of the study, contemplating their implications. They underline the importance of considering both the physical characteristics and cultural contexts when evaluating the acoustics of religious structures. These sections conclude by stressing the significance of a comprehensive understanding of these factors for an accurate acoustic evaluation.

2. Characteristics of the churches under review

There is six historic wooden CC entered on the UNESCO list in 2003. They are located in southern Poland, and each has unique architectural features and histories. The section highlights their distinct characteristics, construction materials, and important historical events related to each church:

- **St. Michael Archangel's Church, Dębno** (DEB) dates back to the late 15th century and is a late Gothic wooden church built with larch and fir wood. It features an izbicowa tower and a shingled exterior. The church consists of a nave and a chancel with a small turret. Distinctive features include various portals and a 19th-century vestibule. Surrounded by a sheltered gallery called soboty. The church is rather small with a total length of 20 meters, the structure comprises an 8.5-meter-long nave and an approximately 6-meter-long sanctuary, offering a harmonious balance for congregants to gather and reflect. The widths of the nave and sanctuary, measuring 7 meters and 5 meters respectively (Fig. 3).
- **St. Leonard's Church, Lipnica Murowana** (LIP) is a 15th-century, humble, wooden structure made from larch wood, measuring 16 meters long, 8 meters wide, and 13 meters high. It features a gable

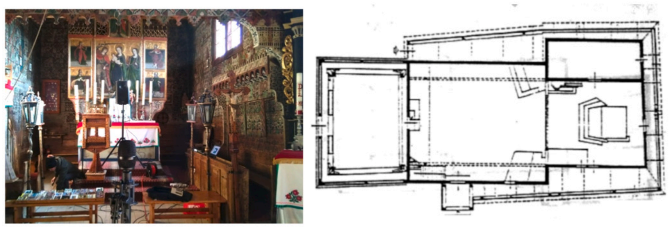

Fig. 3. Interior photograph and floor plan of St. Michael Archangel's Church in Dębno.

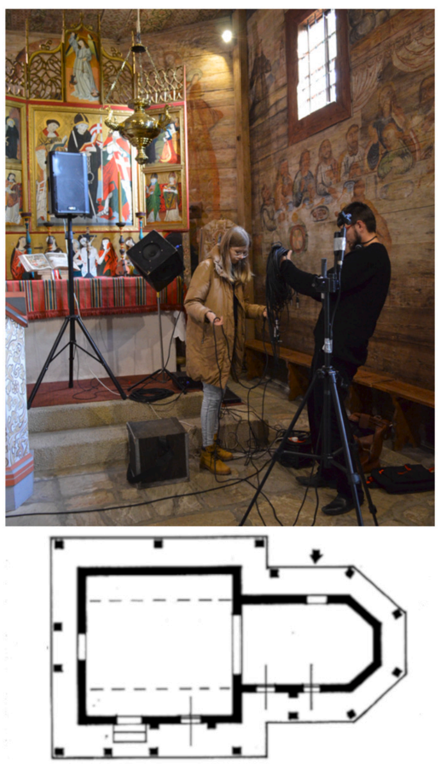

Fig. 4. Interior photograph and floor plan of St. Leonard's Church in Lipnica Murowana.

roof, trilateral chancel, wooden skirt roof, and horizontal log construction. It is also known for abundant polychromes from the 15th to 18th centuries. The interior is divided into a nave for the faithful and a chancel for Mass. The church features unique stencil paintings for educational purposes and is believed to be built on a previous pagan temple site (Fig. 4).

- **Church of the Assumption of the Blessed Virgin Mary and St. Michael the Archangel, Haczów** (HAC) was constructed in the 1450 s, making it the oldest, largest, and best-preserved wooden Gothic church built using log construction in Europe. An overall length of building is 39 meters, it is composed of a 14-meter-long nave and an approximately 12-meter-long sanctuary. The width of the nave, is 12 meters, and the 8.5-meter-wide sanctuary. The 18-meter height of the ridge adds to the monumental scale of the structure. It features unique architecture, such as zaskrzynienia (extended beams of the upper part of the chancel's side walls) and a timber roof truss structure secured by catches located under the eaves. The church also boasts rare 15th-century figural paintings, discovered in 1955. After a Tatar invasion in 1624, the church was reconstructed with a tower-bell, arcades, ridge turret, and new windows (Fig. 5).
- **Church of St. Philip and St. James the Apostles, Sękowa** (SEK) was constructed around 1520, with expansions in the 17th and 18th centuries. It features a log structure with a chancel enclosed on three sides, a distinctive timber roof truss system, and a tower topped by a dome with an octagonal lantern and spherical cupola. The church is noted for its picturesque late-Gothic portals and was severely damaged during WWI, resulting in the loss of many valuable interior elements. The current interior (Fig. 6) largely consists of reconstructions and contemporary additions. A total length of church is 28 meters. The interior consists of a 7.5-meter-long nave and an approximately 8.5-meter-long sanctuary, providing a well-balanced space for worship and reflection. Both the nave and sanctuary feature sufficient widths of 7.5 meters and approximately 5.5 meters, respectively (Fig. 6).
- **Church of All Saints, Blizne** (BLI) is believed to date back to the 14th century, with the current building constructed in the 15th century. The structure features stone foundations, a log construction, and a timber roof truss with carpenters' marks. In 1646, a belfry tower was added, and later a cupola. The church has unique features such as late Gothic ogee arch windows, a lancet arch-shaped and rood arcade. The church in Blizne features consecration crosses and murals dating back to the 16th century. These late-Gothic and Renaissance murals in the chancel depict the various scenes from the life of Christ and the Virgin Mary. A total length of the building is about 33 meters and the church is divided into two main sec-

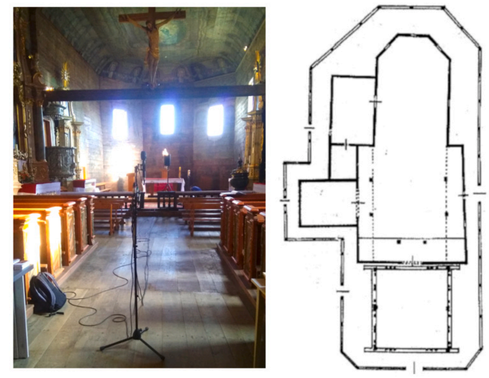

Fig. 5. Interior photograph and floor plan of the Assumption of the Blessed Virgin Mary and St. Michael the Archangel Church in Haczów.

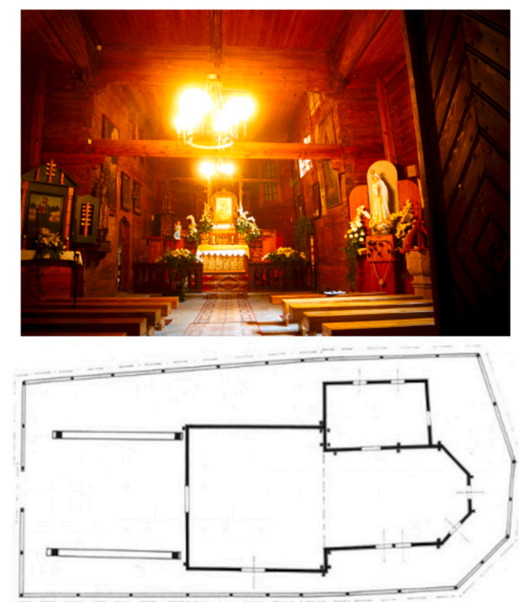

Fig. 6. Interior photograph and floor plan of St. Philip and St. James the Apostles Church in Sękowa.

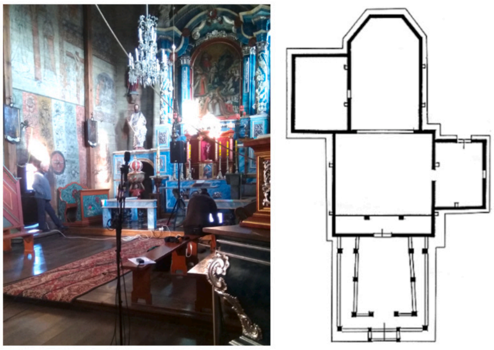

Fig. 7. Interior photograph and floor plan of All Saints Church in Blizne.

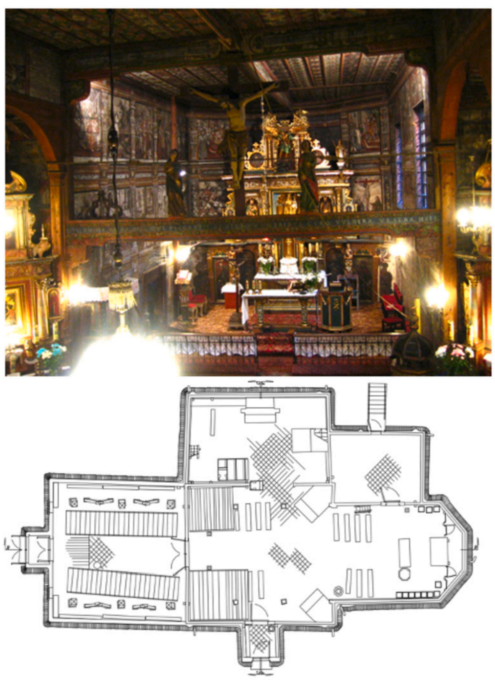

Fig. 8. Interior photograph and floor plan of St. Michael the Archangel Church in Binarowa.

tions: the nave, which measures 11 meters in length and 10 meters in width, and the sanctuary, approximately 12 meters long and 7 meters wide. Additionally, the tower above the nave reaches height of approximately 19 meters (Fig. 7).

- **St. Michael the Archangel Church, Binarowa** (BIN) was established in the 15th century and is a log building, a unique architectural style built with interlocking horizontal logs without nails. The church features a rectangular nave, a narrower chancel closed on three sides, and zaskrzynienie, a structure resembling suspended chests within the nave's ceiling. The tower, built in 1596, is the oldest preserved extension of this type in Poland. The entire structure stretches to a considerable length of 31 meters, incorporating a 10-meter-long nave and an approximately 9-meter-long sanctuary. Both sections offer ample space, with the nave spanning 10 meters in width, while the sanctuary measures around 6.5 meters wide. The ridge of the church reaches a height of 15 meters (Fig. 8).

Wooden OC in Southern Poland were inscribed in 2013 on the UNESCO World Heritage List as a serial Polish-Ukrainian cross-border entry: "The Wooden Tserkvas of the Carpathian Region in Poland and Ukraine" [23]. It is a collection of 16 wooden churches, with eight of them located in Poland:

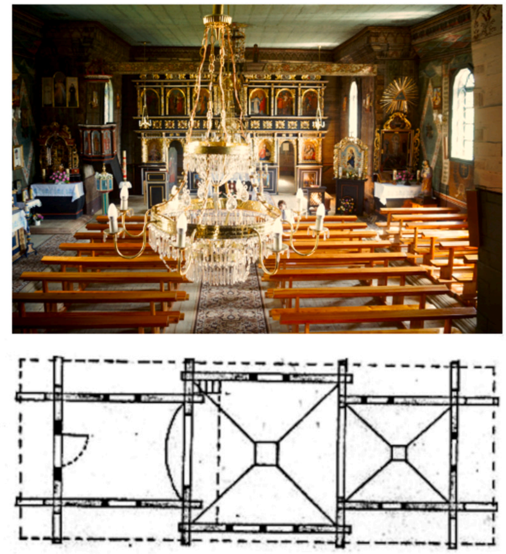

Fig. 9. Interior photograph and floor plan of St. Michael the Archangel Church in Brunary.

- **Church of St. Michael the Archangel, Brunary** (BRU) was built in 1797 and is classified as a West-Lemko church. Its current form is due to a significant reconstruction in 1830-1831, which expanded the church, giving it a distinctive size and elongated silhouette. The walls of the nave and sanctuary are boarded, and the domes, roofs, and tower walls are covered with shingles. The tower above the matroneum is covered with white-painted metal, and all the towers are topped with single crossbeam forged crosses. The church's two-tiered roofs are narrow at the bottom, and it features five windows on both southern and northern sides, and one on the east side, all with rounded upper parts and arched eaves. The entire mass of the building stretches 35 meters in length. The matroneum measures 5 meters in width, while the nave, the central and most expansive part of the church, spans 11 meters in width. The sanctuary, is 6.5 meters wide. The church towers heights: above the matroneum stands at 22 meters, the tower above the nave reaches 20 meters, and the tower above the sanctuary is 15.5 meters tall (Fig. 9).
- **Church of the Nativity of the Theotokos, Chotyniec** (CHO) was built before 1615. It is a log construction, comprising a matroneum, nave, and sanctuary. With large, spherical domes on octagonal bases, the structure is crowned with turrets and forged crosses. The walls are surrounded by roofed arcades, or soboty, with shingles covering the domes and walls. The matroneum is built on a square-like plan, featuring a gallery accessible via external wooden stairs. The nave is the temple's largest and highest part, with six-meter-long sides, while the sanctuary is the smallest and lowest part, measuring four meters wide at its junction with the nave. The original building captivates with harmonious proportions and closely situated spherical domes. The matroneum is 13 meters high and 4.5 meters wide. The nave stands at 16 meters high and approximately 6 meters wide, while the sanctuary is 11.5 meters high and 4 meters wide at its widest point (Fig. 10).
- **Church of St. Paraskeva, Kwiaton** (KWI) was built around the mid-17th century in North-western Lemko style from carefully processed fir wood. Constructed using log building techniques, wooden dowels connect the structure without the use of nails. Shingles cover the light brown walls and onion domes of the towers, with forged single-crossbeam crosses adorning each of the domes. The roof over the nave is three-tiered, while the roof over the sanctuary is two-tiered. The building measures 19 meters in length, with tower heights of 21.5 meters (matroneum), 17.5 meters (nave), and 12 meters (sanctuary). The matroneum is 4 meters

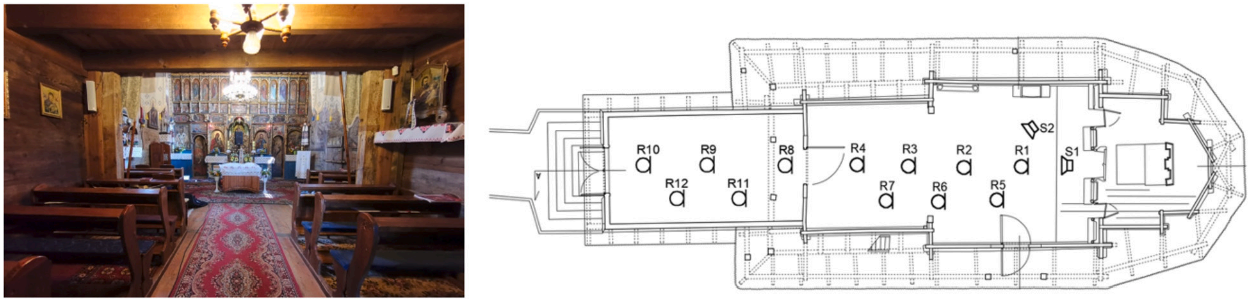

Fig. 10. Interior photograph and floor plan of the Nativity of the Theotokos Church in Chotyniec.

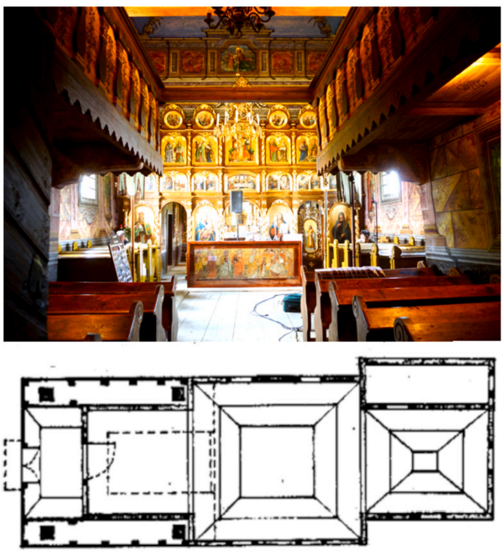

Fig. 11. Interior photograph and floor plan of St. Paraskeva Church in Kwiaton.

Fig. 12. Interior photograph and floor plan of the Intercession of the Theotokos Church in Owczary.

wide, the nave 6.5 meters wide, and the sanctuary 4.5 meters wide (Fig. 11).

- **Church of Pokrov, or the Intercession of the Theotokos, Owczary** (OWC) is a larch wood structure built in 1653, making it one of the oldest West-Lemko churches. Its spherical domes are covered with metal, while the roof and walls are protected by shingles. The church's matroneum, nave, and sanctuary were constructed on a square plan. The roofs over the nave and presbytery are two-tiered. The building measures 20.5 meters in length, with tower heights of 21 meters (matroneum), 17 meters (nave), and 13 meters (sanctuary). The widths of the matroneum, nave, and sanctuary are approximately 7 meters, 7 meters, and 4.5 meters, respectively. The iconostasis created between 1712-1756, is a 7-meter-wide and 5.5-meter-high partition made of wood and decorated with 38 icons arranged in four horizontal rows (Fig. 12).
- **Church St. Paraskeva, Radruż** (RAD) was built in the mid-16th century and renovated in 1720. It features a tripartite floor plan comprising a women's gallery, nave, and sanctuary. Shingles cover the walls, roof, and onion-shaped domes, and log frames provide structural support. The church's interior is adorned with intricate 17th and 18th-century polychromy, showcasing geometric patterns and floral motifs that grace the walls and ceilings. A Baroque iconostasis, crafted in the early 18th century displays elaborate ornamentation, icons, and a central portrayal of the Last Supper. Measuring 25 meters in length, the church's sections have the following dimensions: a 7-meter-wide women's gallery, an 8-meter-wide nave, and a 5-meter-wide sanctuary. The towers reach heights of 7 meters (women's gallery), 18 meters (nave), and 11 meters (sanctuary) (Fig. 13).

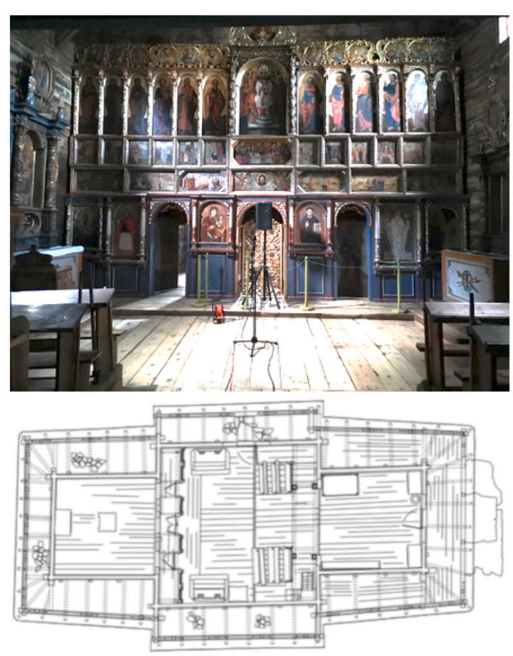

Fig. 13. Interior photograph and floor plan of St. Paraskeva Church in Radruż.

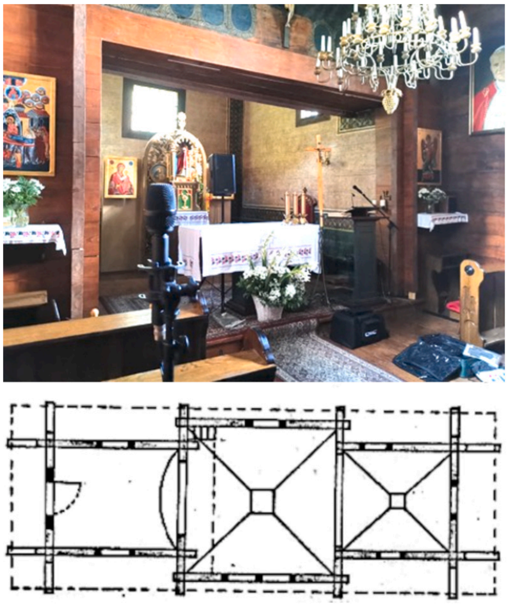

Fig. 14. Interior photograph and floor plan of St. Michael the Archangel Church in Smolnik.

- **Church of St. Michael the Archangel, Smolnik** (SMO) was constructed in 1800 and refurbished in the 19th century. It is divided into three sections: a women's gallery, nave, and sanctuary. Clad in shingles on both the walls and roof, the church's structure is composed of log frames. The polygonal tower crowning the women's gallery and the tripartite tent roof of the nave are distinctive features. A dome atop the sanctuary, adorned with an iron cross, completes the church's appearance. Inside, the church boasts a late Baroque iconostasis crafted in 1800, renowned for its remarkable woodworking and painting. It presents icons in three rows, separated by cornices and topped with a crucifix. The church's dimensions are as follows: a 5.5-meter-wide women's gallery, an 8-meter-wide nave, and a 5.5-meter-wide sanctuary. The total length of the church is 21 meters, while the tower above the women's gallery stands at 17 meters high (Fig. 14).
- **Church of James the Apostle, Powroźnik** (POW) dates back to 1600. It represents the West-Lemko style and features shingles on its walls, roofs, and tower domes. Its modern shape is a result of a 1813 reconstruction. The church comprises a matroneum with a small vestibule, a two-tiered roof over the nave, and a sanctuary with a three-sloped roof. The sacristy, which has 13 square meters and five walls, originally served as the sanctuary. During Operation Vistula and the forced resettlement, the Greek Catholic parish ceased to exist, and the Roman Catholic church took over the building, introducing significant changes to the interior design. The church's dimensions are as follows: the entire building is 21 meters long, with a 4-meter wide matroneum, a 7-meter wide nave, and a 5-meter wide sanctuary. The tower heights above the matroneum, nave, and sanctuary are 21 meters, 16 meters, and 9.5 meters, respectively (Fig. 15).
- **Church of St. Paraskeva, Turzańsk** (TUR) is a wooden church built in 1706. The church represents the traditional Lemko style and showcases the blending of Orthodox and Latin architectural features. The church has a log construction and is divided into three distinct sections: a women's gallery (matroneum), a nave, and a sanctuary. Each section is covered in shingles and features a separate roof. The roof above the nave is two-tiered and consists of a central tent roof and lower side roofs. A polygonal tower with an onion-shaped dome and a metal cross crowns the women's gallery. The interior of the church displays an ornate 18th-century iconostasis, which serves as a visual barrier between the nave and sanctuary. The women's gallery measures 5.5 meters wide, the nave 8 meters wide, and the sanctuary 6 meters wide. The total length of the church is 20 meters, while the tower above the women's gallery reaches a height of 15 meters (Fig. 16).

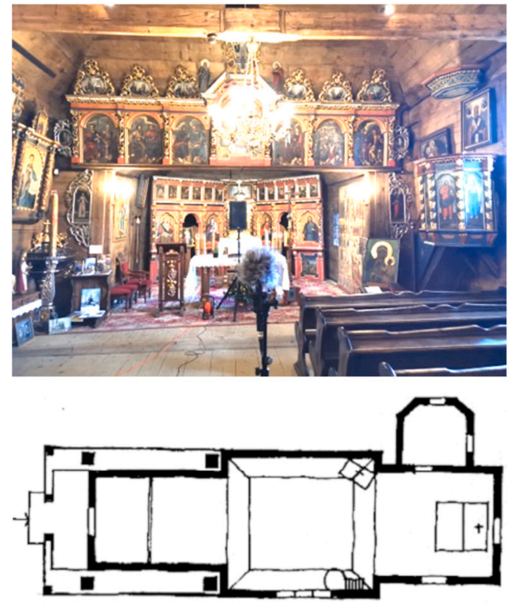

Fig. 15. Interior photograph and floor plan of James the Apostle Church in Powroźnik.

Fig. 16. Interior photograph and floor plan of St. Paraskeva Church in Turzańsk.

All church images presented in Figs. 3–16 were captured by the author. The floor plans are accessible under the CC0 1.0 license from the zabytek.pl website. A comprehensive summary of the churches analyzed, including their respective volumes and floor surfaces, is provided in the Table 1. This summary also introduces the abbreviations that will be consistently employed in the following analyses

3. Measurement method

Measurements of the acoustic parameters were conducted in six UNESCO wooden Catholic Churches (CC) and eight Orthodox Churches (OC) in Southern Poland in 2018 and 2019. The same measurement method employed in the author's previously published works, specifically [9] and [10], has been utilized in this study. The measurements took place under unoccupied circumstances. To ascertain the Spatial Impulse Responses, EASERA software, and MATLAB scripts were employed. Adherence to fundamental standards in room acoustics ISO 3382 [24] and "Guidelines for acoustical measurements in church-

Table 1
Summary of the analyzed churches volumes and floor surfaces together with abbreviations used in the further analyses.

Catholic Churches (CC)	Abbr.	Vol. [m^3]	Floor surf. [m^2]	Dim. (L x W) [m]
St.Michael Archangel's, Dębno	DEB	650	170	8.5 x 6
St.Leonard's, Lipnica Murowana	LIP	700	100	16 x 8
Assumption of the Blessed Virgin Mary and St. Michael the Archangel Haczów	HAC	5000	700	39 x 12
St. Philip and St. James the Apostles, Sękowa	SEK	1400	170	28 x 7.5
All Saints, Blizne	BLI	5000	340	33 x 10
St. Michael the Archangel, Binarowa	BIN	1800	300	31 x 10
Orthodox Churches (OC)				
St. Michael the Archangel, Brunary	BRU	2300	350	35 x 11
Nativity of the Theotokos, Chotyniec	CHO	1050	140	22 x 6
St. Paraskeva, Kwiaton	KWI	1600	170	19 x 6.5
Intercession of the Theotokos, Owczary	OWC	900	140	20.5 x 7
St. Paraskeva, Radruż	RAD	1000	100	25 x 5
St. Michael the Archangel, Smolnik	SMO	450	90	21 x 8
James the Apostle, Powroźnik	POW	850	125	21 x 7
St. Paraskeva, Turzańsk	TUR	1000	200	20 x 8

es" [15] was maintained during measurements. However, due to the main aim of the measurements (SIR capture for auralization) and nature of the spaces, certain changes were introduced. A QSC K10 active loudspeaker was utilized as a substitute for an omni-directional sound source. The maximum level is 130 dB SPL with a frequency response range of 56 Hz - 20 kHz, accounting for a ± 6 dB margin. Its horizontal and vertical coverage (-6 dB) spans 90°, situated between human mouth directivity, as investigated by [25]. The directional characteristics of the QSC K10 loudspeaker, as depicted in Fig. 17, closely resemble the radiation pattern of the human voice across frequencies vital for speech. Consequently, the comparison of parameters other than reverberation time should be cautiously executed. Given the distinct nature of a directional source, the radiation pattern differs from those in studies utilizing omnidirectional source. This discrepancy potentially influences the direct-to-reverberant sound ratio, affecting the overall room acoustic analysis. For Speech Transmission Index (STI) increase of the direct sound at certain locations, can enhance the STI and thus the speech intelligibility in those areas. However, for areas outside of the main radiation lobe of a directional source, the STI can be reduced. Similarly with Clarity index, the focused sound energy from a directional source could improve the Clarity Index for listeners situated in the main radiation lobe, but could potentially reduce clarity for those outside of this area.

A deviation from the standard involved a significantly reduced number of measurement points, necessitated by time constraints associated with accessing the churches. Furthermore, the number of source positions was confined to two or three. The source was consistently situated in front of the iconostasis or altar, along with an additional control position (in close proximity to the main point). These locations typically host concerts, as well as the priest's sermons and chants. The receiver positions were placed in characteristic locations within each church, including: behind the Holy Table in OC or behind the Altar in CC - corresponding to the first rows during concerts, at the midpoint of the temple (at least two positions), beneath the gallery, at the rear of the temple, in the aisles (at least three positions), and in other positions dictated by unique architectural features. An example of a floor plan, depicting the source and receiver locations, is illustrated in Fig. 10. In the remaining churches, a similar and proportionate scheme was employed, scaled according to the building's dimensions. The test signal employed for the measurement process was 10-second logarithmic sine sweep. To measure the spatial aspects of the acoustic field, Sennheiser AMBEO the first-order ambisonic microphone was employed for measurements. Most of the monaural room acoustic parameters were determined based on a B-format pressure component W.

4. Results

The designated acoustical parameters for the examined wooden ecclesiastical structures were computed, encompassing Reverberation Time (T20), Early Decay Time (EDT), Bass Ratio (BR), Treble Ratio (TR), Speech Transmission Index (STI), Clarity C7, Clarity for Music (C80) and Clarity for Speech (C50). Comprehensive explanations of these parameters can be found in authoritative acoustics literature [26], [27]. Subsequent graphical representations (Figs. 18–22) depict the calculated values of the aforementioned parameters, ascertained from all measurement positions. Reverberation and tonal parameters (RT, EDT, BR, TR) are represented as median values, consolidated from all measurement points. Conversely, distance-sensitive parameters (STI, C7, C50, and C80) are presented based on a fixed configuration where the source and microphone are 5 m apart. This configuration was maintained for each object studied. In the context of the specific churches considered in this study, this positioning is optimal from an audience perspective during musical concerts, providing the most representative acoustic response. The clarity parameters, C7, C50, and C80, are broadband averages, computed over the frequency range of 125 Hz to 4 kHz.

Reverberation time plays a pivotal role in sacred architectural spaces, influencing both the aesthetic and functional aspects of these environments. From an aesthetic perspective, the reverberation time contributes to the perceived ambience or 'sacredness' of a space. From a functional perspective, it affects the intelligibility of speech and the quality of music, and thus, has implications for liturgical practices within these spaces [28]. The reverberation time T20 of churches and cathedrals as a function of frequency is depicted in Fig. 18. The values reside within a similar range; however, the churches exhibit a greater dispersion of values. The frequency characteristics are similar for both cathedrals and churches, but the consistency for cathedrals is more pronounced. The church identified as SEK exhibits a relatively elongated reverberation time at lower frequencies. However, this structure has undergone comprehensive reconstruction and is sparsely furnished, which can significantly impact its acoustical properties [29]. The short reverberation time, below one second, observed in two churches (BIN and POW) is attributable to their relatively small size and the significant amount of sound-absorbing elements within their furnishings. Generally, the short reverberation time and frequency characteristics bell-shape in all the studied old wooden temples of the Carpathian region are primarily due to their limited size and the properties of the aged, dry wood. This wood, laden with natural cracks and possessing a porous structure due to insect activity, corrosion, and other natural factors, contributes to a unique acoustic response with high absorption low and high frequensies. Consequently, the reverberation time in these

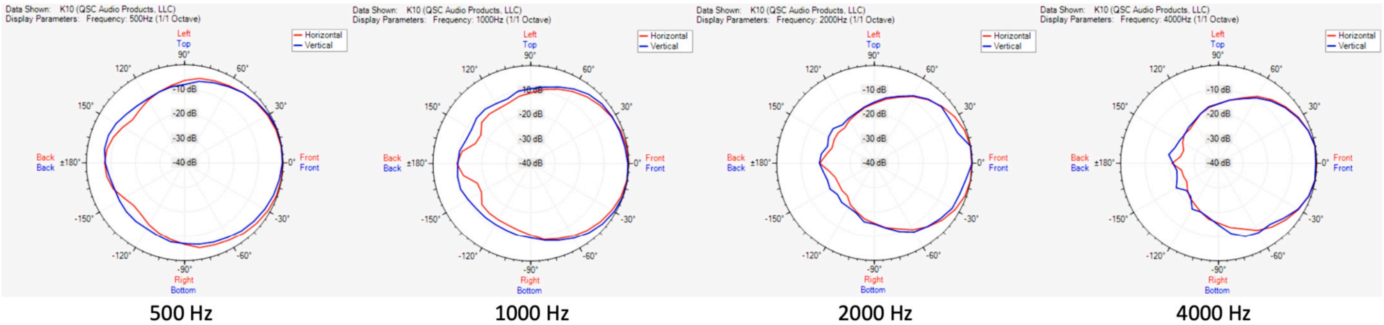

Fig. 17. QSC K10 loudspeaker directivity.

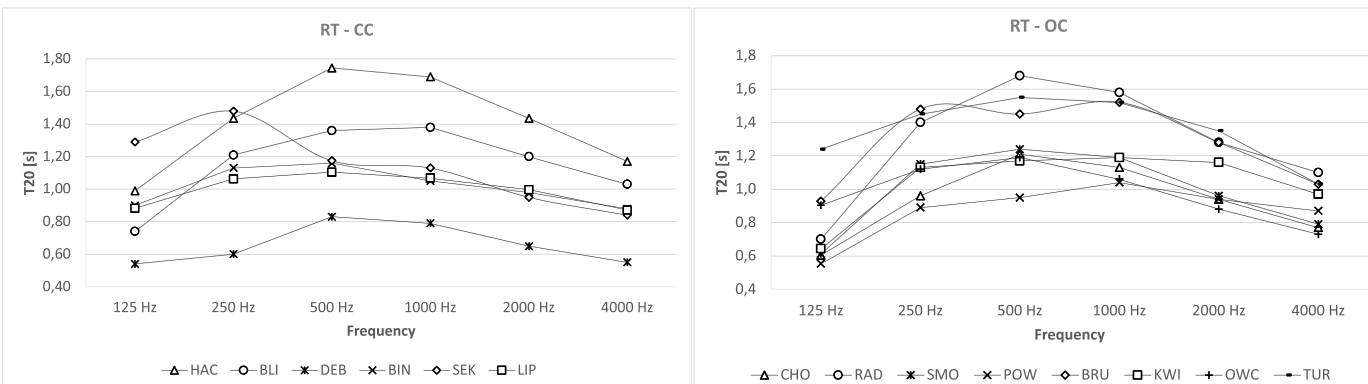

Fig. 18. Frequency characteristics of the reverberation time (T20) in the analyzed wooden churches – comparison of CC and OC.

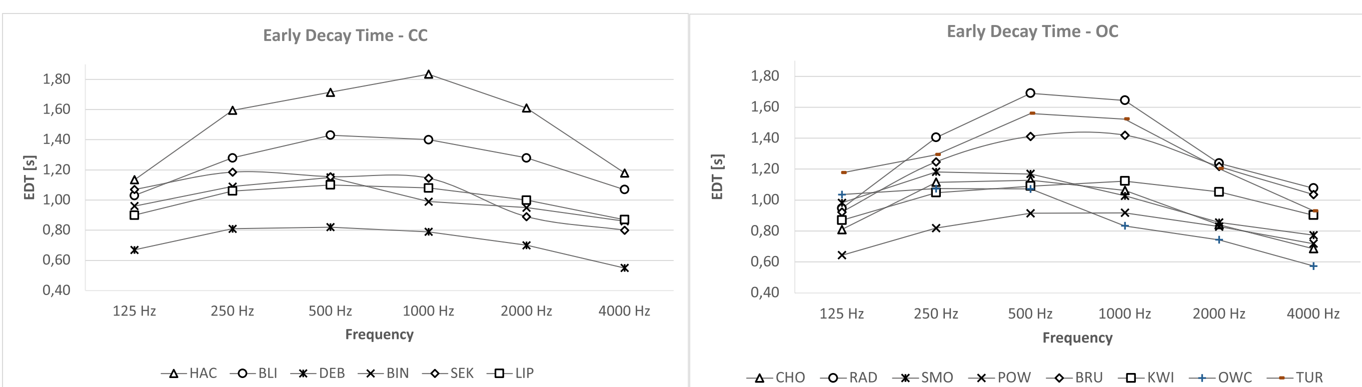

Fig. 19. Frequency characteristics of Early Decay Time (EDT) in the analyzed wooden churches – comparison of CC and OC.

temples is significantly shorter compared to others, especially most European structures which are primarily made of masonry and have a vastly different frequency characteristic and greater reverberation [30].

The Early Decay Time (EDT) is a key acoustic parameter that describes the rate of decay of the sound pressure level in the initial phase after the direct sound has been received. EDT is particularly relevant for understanding the perception of'clarity' or'definition' in a space, affecting the intelligibility of speech and the quality of music [24]. EDT is especially important for music, as it can shape our perception of the timbre and articulation of notes and musical phrases [31]. The EDT parameter exhibits less variation concerning the shape of the frequency characteristics (Fig. 19). Most of the structures, including both the CC and OC, possess EDT peaks in the 500-1000 Hz bands. The characteristics of OC are very similar to each other in terms of their shape and absolute values, which indeed fall "within" the characteristics of CC.

The Bass Ratio (BR) and Treble Ratio (TR) are coloration parameters used in room acoustics to assess the balance of low-frequency to mid-frequency energy (BR) and high-frequency to mid-frequency energy (TR) respectively. These metrics give a sense of the spectral balance and timbral characteristics of a room. They can be thought of as indicators of the "brightness" or "warmth" of a room's acoustic profile [32]. Almost all analyzed CC are characterized by higher values of these coefficients (Fig. 20). The Bass Ratio, in particular, is decidedly higher for all objects, with BIN, SEK, and LIP standing out. This suggests a darker timbral coloration in the wooden CC compared to OC. In all objects, mid frequencies tend to dominate over high frequencies. This could be associated with the architectural design, materials used, or specific acoustical adjustments intended to optimize the liturgical functions of these spaces. The only two objects where the Treble Ratio is close to 1 are OC: POW and KWI. A TR value close to 1 suggests a more balanced frequency response with no significant emphasis on high frequencies relative to mid frequencies. This might indicate a more neutral or "bright" acoustic character in these spaces [33].

The Speech Transmission Index (STI) is a quantitative measure of speech intelligibility, representing the degree to which a transmitted speech signal is degraded by reverberation, ambient noise, and other

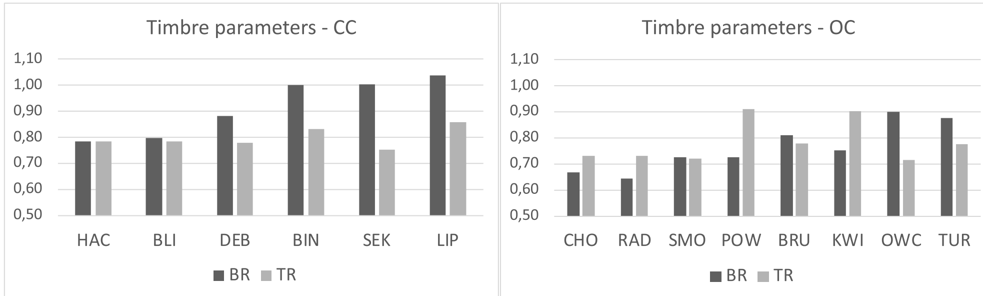

Fig. 20. The Bass Ratio (BR) and Treble Ratio (TR) of the analyzed wooden churches – comparison of CC and OC.

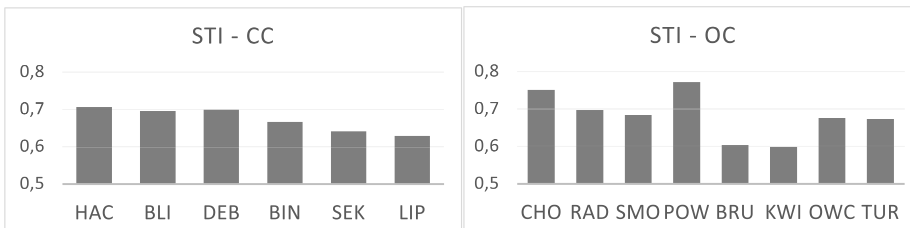

Fig. 21. Speech intelligibility (STI) of the analyzed wooden churches – comparison of CC and OC.

factors. STI values range from 0 to 1, with higher values indicating better speech intelligibility [34].

For CC, the STI values range from 0.6 in LIP to 0.7 in HAC (Fig. 21). All the CC churches display fairly high STI scores (above 0.6), suggesting an overall good level of speech intelligibility within these spaces. HAC, BLI, and DEB, with the highest scores around 0.70, may provide especially favorable conditions for clear speech transmission. SEK and LIP, despite having the lowest STI values among CC, still show a decent level of speech intelligibility. Looking at OC, the STI values extend from 0.60 (BRU, KWI) to 0.8 (POW), indicating a considerable variation in speech transmission quality. POW stands out with the highest STI value, suggesting it might offer exceptionally clear conditions for speech communication. BRU and KWI, despite having the lowest STI values among OC, have scores around 0.6 that still suggest a satisfactory level of speech intelligibility.

Interestingly, the overall STI values for OC are slightly higher compared to those for CC, as shown in Fig. 21. This is somewhat surprising given that the Orthodox liturgy is largely sung, rather than spoken, as opposed to Catholic churches, where the spoken word and its intelligibility are the dominant elements. However, it's important to consider the historical context. At the time the analyzed structures were built, Latin and Church Slavonic were the liturgical languages in use. In this regard, Orthodox church goers understood significantly more due to the similarity of Church Slavonic to the local language, as opposed to participants of the Tridentine Mass, conducted in Latin, which was largely incomprehensible to the majority of the faithful [35]. However, it is also possible that the higher STI values reflect the different architectural styles of the two types of churches, with the distinctive architectural features of Orthodox churches, such as the domes and iconostases, contributing to the improved acoustical clarity [36]. Further research would be needed to fully understand these differences. In any case, these findings underscore the importance of considering both the physical and cultural contexts when evaluating the acoustics of religious structures, and they highlight the complex interplay between acoustics, architecture, liturgy, and language in shaping the sonic environment of a space [37].

The highest values of C80, indicative of a clear and distinct perception of individual sounds or musical notes, were noted in CC: HAC, BLI, and DEB (ranging between 10 dB and 13 dB - Fig. 22). The remaining churches present C80 values between 5 dB and 10 dB, suggesting a more balanced energy distribution between early and late arriving sound [38]. C80 values exceeding 2 dB generally suggest that a space may not be well-suited for certain types of music, as higher values indicate less reverberation and greater clarity. However, it's essential to consider both the type of music and the cultural context. While a high C80 value might be less suitable for specific genres of orchestral music it could be fine for vocal or chamber choral music commonly performed in these churches. In the context of the C50 parameter, essential for clear speech intelligibility, there is a wide range of values for CC, ranging from 3 dB (LIP) to 12 dB (HAC). This suggests varying levels of speech clarity across these churches, which could impact the efficacy of spoken word communication during services [39]. The C7 parameter values for CC span from -3 dB (LIP) to 8 dB (HAC). Most of the CC churches show positive C7 values, with an exception of LIP. This indicates an early to late sound energy ratio that might favor clearer sound fields. The C7 acoustic parameter is similar in concept to the more commonly used C50 and C80 indices. C7 focuses on the sound energy within the first 7 milliseconds following the direct sound. The short time window makes C7 an appropriate parameter for environments where almost immediate sound reflection is critical for perceived sound quality like small or non-reverberant spaces. It is designed to quantify the clarity or definition of sound in a room. Lower values of C7 compared to C50 and C80 in most of the churches suggest that these spaces may be more suited for music and speech applications that require a longer initial time delay gap and more diffusive sound fields. In terms of the OC churches, the C80 values lie within a range of 6 dB to 12 dB. For the C50 parameter, values remain fairly consistent, fluctuating around 6-9 dB, with an exception of BRU where it approximates to 4 dB. This suggests a generally good level of speech clarity in most OC, with BRU possibly needing some adjustments to enhance spoken word communication. The C7 parameter values for OC are all positive, with an exception for KWI. This signifies an overall favorable early to late sound energy ratio, which could contribute to a more defined and clear sound field.

Based on the geometric data compiled in Table 1 and the average reverberation time values (at 500 and 1000 Hz) in the examined buildings, the relationship between these parameters was determined in Fig. 23 to analyze the impact of the sizes of the studied buildings on a key acoustic parameter, i.e., reverberation. In addition, root mean square logarithmic approximations were calculated for the sets of OC and CC. The results indicate a strong dependency (R2 = 0.77) of the reverberation time on the volume of wooden CC. However, despite the converging shape of the approximation function for OC, the coefficient

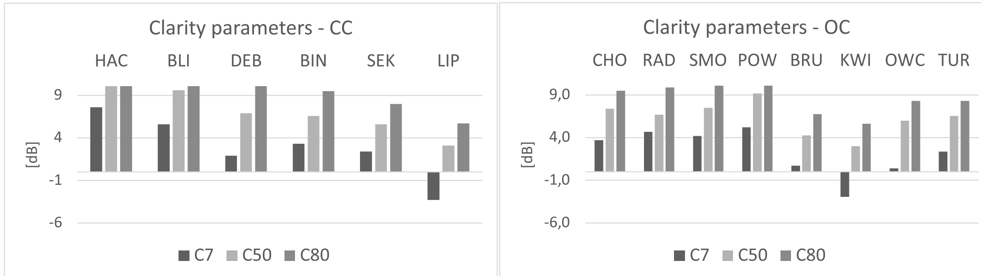

Fig. 22. Clarity C7 and for speech (C50) and music (C80) in the analyzed wooden churches – comparison of CC and OC.

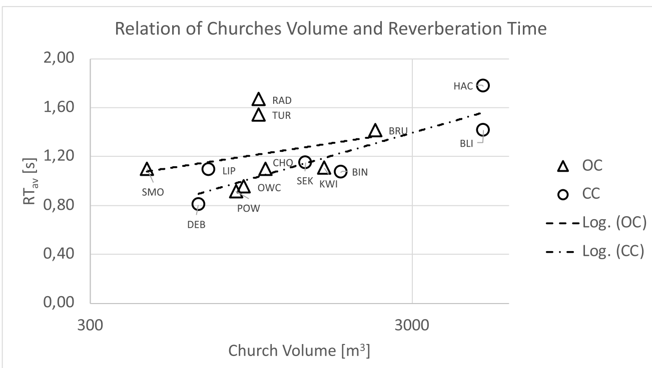

Fig. 23. Relation of average Reverberation Time to churches volume – comparison of CC and OC together with logarithmic approximation lines.

of determination value is R2 = 0.09 only. It can be observed that the RAD and TUR objects significantly deviate from the calculated trend. The reverberation time in these temples is significantly longer than that in the OC with a similar volume. For all considered data, R2 = 0.35, which can be interpreted as a relatively strong correlation between volume, sound absorption, and reverberation, implying that most of the demonstrated differences between the acoustic parameters of wooden CC and OC result from other factors. These other influencing factors could include a variety of variables, such as the material composition and structural design of the churches, the presence of absorptive materials in the interior (e.g., rugs, curtains), or even the degree of maintenance and preservation of the building. Further research might seek to examine these potential influencing factors in greater detail to fully understand the unique acoustic characteristics of these historic wooden churches.

5. Discussion

The results of the study, while informative, are subject to several limitations that warrant consideration. The use of a directional sound source posed significant challenges in interpreting the results and comparing them to the findings of other studies. While a directional source can potentially enhance parameters like STI and Clarity at certain locations, it may also compromise these parameters in other areas of the room. On the orher hand, according to the author’s previous work [40], the use of a directional source does not significantly influence acoustic parameters in a medium-sized reverberant church

The absence of people during the measurements has notably affected the results. The presence of an audience can significantly change the acoustic properties of a space due to sound absorption. Finally, the limited number of measurement points and time constraints posed difficulties in achieving a thorough geometric reporting of results. The acoustic properties of a space are profoundly influenced by its geometry, and having a limited number of measurement points may not provide a complete picture of the room’s acoustic characteristics. In future investigations, it would be beneficial to conduct more measurements over a longer period and at various points within the room to obtain a more comprehensive understanding of the acoustic environment.

6. Summary and conclusions

This study provides a comprehensive analysis of the acoustic characteristics of selected wooden UNESCO Orthodox and Catholic Churches in Poland. It builds on previous research [9], [10] and extends the understanding of how the structural design and materials used in these historic religious buildings contribute to their distinct acoustic properties. The festival Muzyka Zaklęta w Drewnie (Music Enchanted in Wood), which takes place in most of the analyzed churches, is a vivid example of how understanding the acoustics of these heritage sites can enrich cultural experiences [2]. The immersive, high-definition sound profiles provided by the acoustic evaluations enhance the visitor’s appreciation of the music performed, creating a truly multisensory experience that binds culture, history, and architecture together. Notably, the findings reveal significant acoustic differences between the OC and CC, with the latter demonstrating a greater degree of acoustic variability. This diversity in the acoustic profiles of the CC might reflect the different architectural and historical contexts in which these buildings were constructed. The influence of diverse geographical locations, construction materials, local traditions, and religious practices might have contributed to the observed acoustic variability. Interestingly, despite the largely sung nature of Orthodox liturgy, Speech Transmission Index (STI) values were noticeably higher for OC compared to CC. These results might reflect the different architectural features of Orthodox churches and their impact on acoustical clarity. The observed acoustical characteristics might also have historical implications concerning the liturgical languages in use at the time these churches were built. This research has important implications for the preservation and management of cultural heritage sites. The acoustic properties of a building are an integral part of its cultural value, providing insight into past societies, technologies, and artistic traditions. It also opens up possibilities for using these unique acoustic environments in contemporary music performances, as exemplified by the Music Enchanted in Wood festival. In conclusion, this study underscores the complex interplay between architecture, materiality, history, and acoustics in shaping the sonic environments of these remarkable heritage sites. It highlights the value of interdisciplinary research in understanding and preserving our cultural heritage, offering new perspectives on the dialogue between past and present, tradition and innovation, in the field of architectural acoustics. Future research could further explore the specific factors contributing to the acoustic diversity observed among the CC, as well as the impact of various conservation and preservation practices on the acoustics of these historic buildings.

CRediT authorship contribution statement

Paweł Małecki: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] Unesco world heritage list, Retrieved May 16, https://whc.unesco.org/en/list/, 2023.
[2] M. W. A. R. Muzyka, Retrieved May 16, http://www.drewniana.malopolska.pl/?page=muzyka&run=multilang, 2023.
[3] Krasny P. Orthodox church architecture on Ruthenian lands. Kraków: Universitas; 2003.
[4] P. K. F. Y. channel, Retrieved May 16. https://www.youtube.com/@penikultury2421/videos, 2023.
[5] D. website Acoustic survey, Retrieved May 16, https://digitalunesco.pl/acoustic-survey/, 2023.
[6] Mijic M, Sumarac-Pavlovic D. Acoustical characteristics of old wooden churches in Serbia. J Acoust Soc Am 2000;108:2648.
[7] Mijic M. Serbian orthodox church - an acoustical view. In: Proceedings of 17th ICA; 2001.
[8] Elicio L, Martellotta F. Acoustics as a cultural heritage: the case of orthodox churches and of the "Russian church" in bari. J Cult Heritage 2015;16:912–7.
[9] Małecki P, Wiciak J, Nowak D. Acoustics of the orthodox churches in Poland. Arch Acoust 2017;42:579–90.
[10] Kosała K, Małecki P. Index assessment of the acoustics of orthodox churches in Poland. Appl Acoust 2018;130:140–8.
[11] Álvarez Morales L, Girón S, Galindo M, Zamarreño T. Acoustic environment of andalusian cathedrals. Build Environ 2016;103:182–92.
[12] Álvarez Morales L, Zamarreño T, Girón S, Galindo M. A methodology for the study of the acoustic environment of catholic cathedrals: application to the cathedral of malaga. Build Environ 2014;72:102–15.
[13] Álvarez Morales L, Martellotta F. A geometrical acoustic simulation of the effect of occupancy and source position in historical churches. Appl Acoust 2015;91:47–58.
[14] Martellotta F. Understanding the acoustics of papal basilicas in Rome by means of a coupled-volumes approach. J Sound Vib 2016;382:413–27.
[15] Martellotta F, Cirillo E, Carbonari A, Ricciardi P. Guidelines for acoustical measurements in churches. Appl Acoust 2009;70:378–88.
[16] Martellotta F. Subjective study of preferred listening conditions in Italian catholic churches. J Sound Vib 2008;317:378–99.
[17] Kosała K. Calculation models for acoustic analysis of St. Elizabeth of Hungary church in Jaworzno Szczakowa. Arch Acoust 2016;41.
[18] Kosała K, Engel ZW. Assessing the acoustic properties of roman catholic churches: a new approach. Appl Acoust 2013;74:1144–52.
[19] Valière JC, Palazzo-Bertholon B, Polack JD. Acoustic pots in ancient and medieval buildings: literary analysis of ancient texts and comparison with recent observations in French churches. Acta Acust Acust 2013;99:70–81.
[20] Galindo M, Zamarreño T, Girón S. Speech intelligibility in mudejar-gothic churches. Acta Acust Acust 2000;86:381–4.
[21] Carvalho AP, Morgado AE. Relationships between speech intelligibility and objective acoustical parameters for architectural features in catholic churches. J Acoust Soc Am 1997;101:3051–2.
[22] Lubman D, Wetherill E. Acoustics of worship spaces. New York: American Institute of Physics; 1985.
[23] World heritage list - wooden tserkvas of the Carpathian region. https://www.worldheritagesite.org/list/Wooden+Tserkvas+of+the+Carpathian+Region, 2013.
[24] ISO 3382-1, Geneva: International Organization for Standardization; 2009.
[25] Soeta Y, Ito K, Shimokura R, Sato S, Ohsawa T, Ando Y. Effects of sound source location and direction on acoustic parameters in Japanese churches. J Acoust Soc Am 2012;131.
[26] Barron M. Auditorium acoustics and architectural design. New York: Spon Press; 2009.
[27] Rossing T. Handbook of acoustics. Stanford: Springer; 2007.
[28] Berardi U, Cirillo E, Martellotta F. A comparative analysis of acoustic energy models for churches. J Acoust Soc Am 2009;126:1838–49.
[29] de Sant'Ana DQ, Zannin PHT. Acoustic evaluation of a contemporary church based on in situ measurements of reverberation time, definition, and computer-predicted speech transmission index. Build Environ 2011;46:511–7.
[30] Sukaj S, Bevilacqua A, Iannace G, Lombardi I, Parente R, Trematerra A. Byzantine churches in Albania: how geometry and architectural composition influence the acoustics. Buildings 2022;12.
[31] Beranek LL. Concert and opera halls: how they sound. Acoustical Society of America; 1996.
[32] Kuttruff H, Acoustics Room. fifth edition. Spon Press; 2009.
[33] Bradley JS. Review of objective room acoustics measures and future needs. Appl Acoust 2011;72:713–20.
[34] Petersen CM, Rasmussen B. Acoustic design of open plan schools and comparison of requirements. In: Joint Baltic-Nordic Acoustics Meeting 2012. Nordic Acoustic Association; 2012.
[35] Meyendorff J. Rome, constantinople, Moscow: historical and theological studies. Pro Eccles 1999;8:372–4.
[36] Ware T. The Orthodox Church: an introduction to eastern Christianity. UK: Penguin; 1993.
[37] Blesser B, Salter LR. Spaces speak, are you listening. J Audio Eng Soc 2007;55:202–3.
[38] Beranek LL. Concert halls and opera houses: music, acoustics, and architecture. 2nd ed. New York: Springer-Verlag; 2004.
[39] Bradley JS. Using iso 3382 measures, and their extensions, to evaluate acoustical conditions in concert halls. Acoust Sci Technol 2005;26:170–8.
[40] Małecki P, Zastawnik M, Wiciak J, Kamisiński T. The influence of the measurement chain on the impulse response of a reverberation room and its application listening tests. Acta Phys Pol A 2011;119:1027–30.